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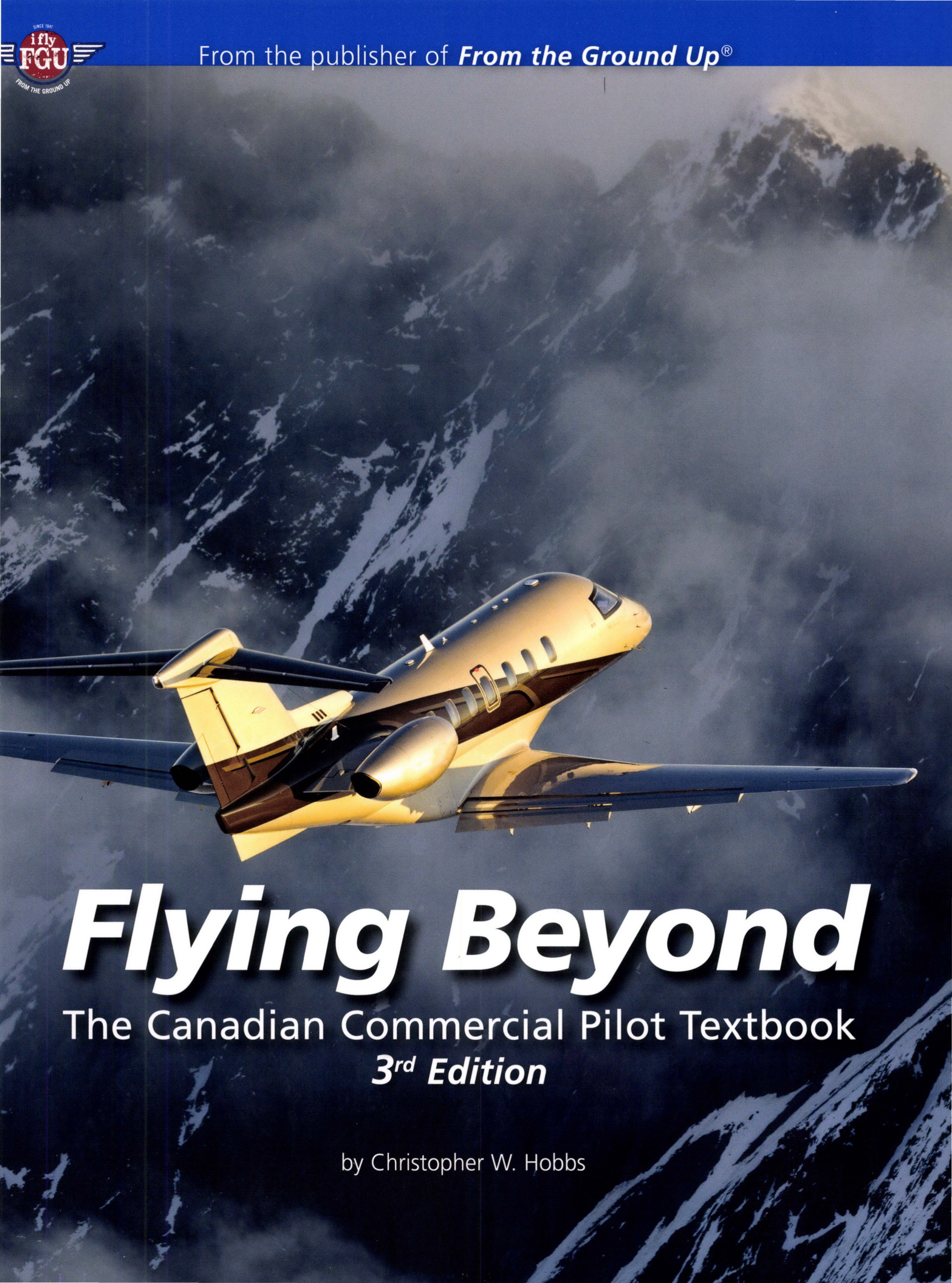

Flying Beyond

The Canadian Commercial Pilot Textbook

3rd Edition

by Christopher W. Hobbs

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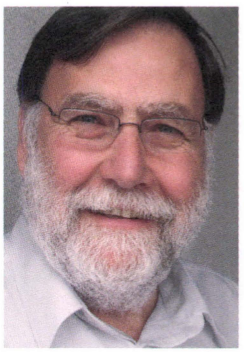
Published by Aviation Publishers Co. Ltd.

About the Author



CHRIS HOBBS was born and raised in the small village of Godmanchester, not far from the university town of Cambridge, in eastern England. He attended Queen Mary, University of London, one of the U.K.'s leading research-focused higher education institutions. There, he earned an Honours Bachelor of Science Degree in Pure Mathematics and Mathematical Philosophy.

A mathematician by training and a software safety engineer by profession, Chris has worked extensively in the field of software development for safety-critical devices: medical devices, railway signalling systems and autonomous cars.

His life as a pilot took flight via an interest in sailplanes. Chris learned to fly gliders in Wales before moving to Canada where he continued his flying activities by learning to fly powered aircraft. Chris was one of the first individuals in Canada to hold a Recreational Pilot Permit. Shortly thereafter, he upgraded to a Private Pilot Licence. Chris now holds a Commercial Pilot Licence, and carries both instrument and instructor ratings.

Chris has years' worth of experience in the teaching of PPL, CPL, and IFR groundschools. His teaching methods are highly-regarded, as are the written materials he has developed to enhance his in-class instruction. Having also authored titles in the field of mathematics and software design, *Flying Beyond: The Canadian Commercial Pilot Textbook* is a product of Chris's thorough background both as a dedicated instructor, and as a very active and proficient pilot.

Chris is based in Ottawa, Ontario, Canada. He flies from his home base, the Rockcliffe Flying Club at which he is a safety advisor, educator and long-standing active member. The Club is located at historic Rockcliffe Airport along the shores of the Ottawa River.

FLYING BEYOND, 3rd Edition
THE CANADIAN COMMERCIAL PILOT TEXTBOOK

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Foreword

So you want to be a Commercial Pilot...

If you want to fly beyond the requirements of the Private Pilot Licence (PPL) and obtain your ticket to fly as a Commercial Pilot Licence (CPL) holder, you need to become a craftsman of your trade.

Consolidating what you have learned to date and honing your skills are the next steps towards becoming a thoroughly skilled, safety-conscious, well-rounded and fully knowledgeable professional pilot.

The CPL allows you to do so much more than you've done before. It opens a door to a career: charter and air taxi, aerial surveying, forest fire detection, medical evacuation, airborne traffic watch, glider towing, banner towing, parachute dropping, flight instructing, and so much more. As a well-prepared and newly minted CPL holder, you are ready for your first job as an aviator.

In this latest edition of Flying Beyond, author Chris Hobbs delves as deeply and intricately as ever into aeronautical theory and practice for commercial pilots. His customary descriptive precision and extensive scope of content continue to inform in ways that are unique to his writing style and reflective of his profound grasp of his subject matter. High standards and attention to detail are hallmarks of Chris' writing and instructional principles.

From their reading of Flying Beyond, Third Edition, readers will take a large and crucial step towards polishing their knowledge and broadening their boundaries to becoming better, more informed, and conscientious skilled professionals. Fly beyond where you've been before, and build upon the foundations you've established up until now. The gateway to your career starts here.

Aviation Publishers Co. Limited

Introduction

Focus

A textbook covering the topics tested by Transport Canada's *Commercial Pilot (Aircraft)* written examination could be focussed in different ways.

Some students see the commercial written examination and flight test as more difficult versions of the private equivalents. To some extent this is justifiable: the study topics specified by Transport Canada are largely the same, with additional depth.

Other students see the Commercial Pilot Licence as a step towards a career in aviation. These students are looking for broader knowledge, even when it goes beyond what is strictly needed for the examination.

While covering the topics required to pass the written examination, this book specifically addresses the second of these audiences. It contains substantially more information than is required to pass the examination, including background information needed by a rounded and knowledgeable pilot.

Origin

The first edition of this book emerged from notes used for several generations of commercial pilot ground schools, being improved after each from class feedback.

Structure

Generally, the topics in this book are presented in the order given in Transport Canada's *Study and Reference Guide*. However, in some cases it has been convenient to rearrange the order to bring related topics together. By referring to the index and table of contents at the top of each chapter, you will find every item in the Transport Canada syllabus explicitly addressed.

First Edition

I am particularly grateful to Alison Hobbs, a wonderful right-seat companion, who has read every word of this book, making corrections of structure, grammar, spelling and consistency.

I am also grateful for the constructive criticism of Claude Béland, Don Buchan, Bill Carscallen, Laurie Davis, Marty Densmore, Bill Fox, Kathy Fox, Alan Graves, Keith MacIsaac, Jeff Nerenberg, Jean René de Cotret, Nicolas Roome and the students in many ground schools on whom drafts were tested. The proof-reading carried out by Marty and Nicolas was particularly meticulous, and their suggestions for content improvement very useful.

Second Edition

Publishing a new edition allowed me to make corrections, change outdated material and add new sections. I am grateful to Martin Tubbesing for email exchanges that led to a reworking of sections 11.3.11 and 11.5.7 and to Les LeBrun for many improvements. New sections included skew-T charts, the Carrington Event and expanded descriptions of ADS-B and weather forecasting models.

A difficult decision was whether to include electrical drive in the chapter on engines. As I prepared the second edition, at least one electrically-powered light aircraft was available, and large manufacturers, such as Boeing, were supporting research into electrical power for airliners.

I also restructured some material, in particular the navigation sections. Reflecting the current reliance on radio navigation rather than pilotage, I rearranged the material into three chapters: chapter 6 covering pre-flight planning, chapter 7 covering radio navigation and chapter 8 covering pilotage. Chapter 8 is likely to be of more use in an examination room than in the air, particularly at the commercial pilot level.

Third Edition

Regulations and technologies change and many of these changes have been reflected in this edition. Some changes occurred faster than the second edition anticipated (e.g., the move to the ICAO NOTAM format and the decommissioning of VORs and NDBs) and other changes occurred more slowly (e.g., the adoption of electric motors to replace turbines and reciprocating engines, and the introduction of ADS-B into Canada). One area where change has been particularly slow is in the syllabus for the Commercial Pilot Licence written examination. It is unlikely that many pilots determine drift by drawing 10° drift lines on paper maps or apply the double track error method to regain track, but these are still on the syllabus and so are still included in this book.

I dedicate this book to Alison
who has taught me so much, most
of all about myself.

师傅领进门，修行靠自身

The teacher can open the door but students enter by themselves.

(Chinese Proverb)

Chapter 1

Human Factors: Psychology

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1.1 What are Human Factors?

Of the topics covered in Transport Canada's Commercial Pilot examination, Human Factors is probably where the most on-going research is taking place. New studies and techniques are appearing regularly and it is a fascinating and ever-changing area to investigate. The ICAO Digest No. 1[1] describes the importance of Human Factors in these terms:

> *Human behaviour and performance are cited as causal factors in the majority of aircraft accidents. If the accident rate is to be decreased, Human Factors must be better understood and the knowledge more broadly applied. The expansion of Human Factors awareness presents the international aviation community with the single most significant opportunity to make aviation both safer and more efficient.*

The publication goes on to emphasise that the study of Human Factors is not solely a medical discipline:

> *Many of the early concerns in aviation were related to the effects on people of noise, vibration, heat, cold and acceleration forces. Usually, the person nearest at hand with a knowledge of physiology was a physician; this may have generated one of the more persistent misconceptions about Human Factors, the belief that it is somehow a branch of medicine. Yet half a century ago work was expanding on the more cognitive aspects of the flying tasks and this trend has continued and is outside the scope of medicine. Optimizing the role of people in this complex working environment involves all aspects of human performance and behaviour: decision-making and other cognitive processes; the design of displays and controls and flight deck and cabin layout; communication and computer software; maps and charts; and the field of documentation such as aircraft operating manuals, checklists, etc.*

Reflecting the division of emphasis between the medical and the psychological, this book divides the topic into two parts:

1. The psychological aspects of flying (handling stress, error, external threats, etc.). These are covered in this chapter.

[1] Reprinted by the Safety Regulations Group of the Civil Aviation Authority and available on the Internet

2. The effects of the flying environment (altitude, noise, illusions, etc.) on the physiology of the pilot. These are covered in chapter 2.

One of the main open areas in the study of Human Factors is the way in which pilots, mechanics, air traffic controllers and others associated with safety in the air should balance operational efficiency with safety. Efficiency is often measured in terms of dollars and is quantifiable; safety is generally not quantifiable. A pilot faced with a go/no-go decision in the face of bad weather has to balance the financial cost (easily calculated in dollars) of not taking off—the cost of hotel rooms for the passengers, the cost of not having the aircraft in the right place for its next flight—against a "feeling" that safety would be compromised by departing. As Sidney Dekker says:[2]

> *Emphasis on local efficiency or cost-effectiveness pushes operational people to achieve or prioritize one goal or a limited set of goals (e.g., customer service, punctuality, capacity utilization). Such goals are typically easily measurable, whereas it is much more difficult to measure how much is borrowed from safety.*

Exam Hint 1 *While Human Factors is one of the most important parts of the Commercial Pilot Course, it is also one of the most difficult on which to set multiple-choice questions. The questions on the written examination tend to concentrate on a limited number of areas where multiple-choice questions can be created: the symptoms of hypoxia, the illusions caused by narrow or wide runways, the number of hours that need to pass after giving blood or scuba diving before flying, the meaning of letters in "DECIDE", etc. Many of the important aspects of Human Factors, for example pilot decision-making, have no clear-cut answers and are therefore inappropriate for multiple-choice questions. Even though the examination questions may be very straightforward, it is strongly recommended that you be aware of the factors discussed in this chapter—it will improve your flight safety.*

1.2 Further Resources

Appendix B on page 341 contains transcriptions of three dialogues that took place during aircraft incidents. They are referred to at various points in this chapter, and are useful for classroom discussion.

[2] In *"Failure to adapt or adaptations that fail: contrasting models on procedures and safety"*, Applied Ergonomics 34.

In addition to a flow of papers tracking the continuing research, there are numerous books on the topic of psychological Human Factors in aviation, including the following:

- *Human Factors in the Training of Pilots* by Jefferson M Koonce, ISBN 978-0-415-25361-1
- *Human Factors for Aviation: Basic Handbook* written and published by Transport Canada, ISBN 0-660-16650-0
- *Human Factors for Aviation: Advanced Handbook* written and published by Transport Canada, ISBN 0-660-16656-9
- *They Called it Pilot Error: True Stories Behind General Aviation Accidents* by Robert L Cohn, ISBN 978-0-830-64463-6
- *Human Factors for General Aviation* by Stanley R. Trollip, Richard S Jensen, ISBN 978-0-884-87138-5

Each of these brings a different perspective but, if you were to buy only one, Koonce's book is probably the most useful. Koonce is an active pilot, researcher and flight instructor and provides an excellent balance of theory and practice. Koonce's book also contains a number of wise and insightful comments and maxims that add to the value and quality of its content.

Although not specifically aimed at pilots, James Reason's book *Human Error* (ISBN 978-0-521-31419-0) and Sidney Dekker's *The Field Guide to Understanding Human Error* (ISBN 978-0-7546-4826-0) are also useful in understanding why pilots make mistakes.

1.3 The Threat & Error Model

1.3.1 Introduction to the Model

Threat and Error Management is a structure within which the response of pilots to external events (threats) and their own errors can be analysed and improved. The first sets of observations within this structure were made in the mid 1990s by researchers from the University of Texas, USA, who studied pilots flying scheduled services for Continental Airlines. Since then, studies have been carried out on many airlines around the world.

As its name suggests, *Threat and Error* Management concentrates on two topics:

1. **Threats.** These are events not caused by the flight crew that increase the operational complexity of the flight, and require the crew to do something to maintain safety margins.

   As illustrated in figure 1.1, threats can be divided into those from the external environment (e.g.,

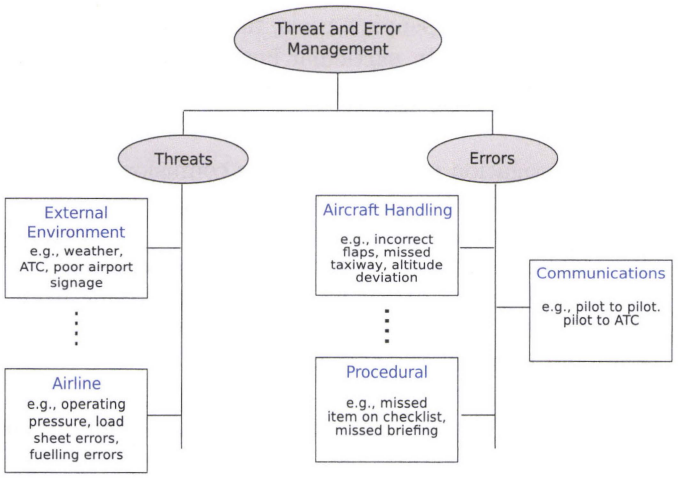

Figure 1.1: Classification of Threats and Errors

adverse weather, poor signage at airports, language difficulties with ATC, radio congestion, etc.) and those from the airline itself (operating pressures, maintenance problems, information missing from manuals, etc.).

2. **Errors.** Members of the flight crew make errors: they take actions that reduce safety margins or increase the probability of adverse events on the ground or in flight.

   Errors include aircraft handling errors (flying at the wrong altitude, setting flaps wrongly, taxiing along the wrong taxiway, passing a hold line, failing to switch fuel tanks, etc.), procedural errors (missing a checklist item, calculating weight and balance incorrectly, etc.) and communications errors (missing an ATC call, misinterpreting an ATC call, copying a clearance wrongly, failing to communicate clearly to another crew member, etc.).

Some of this research has been questioned by Sidney Dekker. In his book *The Field Guide to Understanding Human Error,* he points out that follow-up studies carried out on Air Traffic Controllers have found that error counting is very subjective and imprecise.

Section 1.4 of this book discusses why pilots make errors, and how the impact of errors can be minimised. Section 1.5 describes some techniques for dealing with threats. These two concepts are not independent: an error will often lead to a threat and a threat will often overload a pilot and cause him or her to make an error.

1.3.2 Reading Incident Reports

One way of becoming familiar with the interplay of threats and errors in flight is to study incident reports. These reports appear on various government websites and in many aviation magazines but it is easy to read them with a sense of superiority and invulnerability: "I'm sure I would never have done that." Indeed, there are some incident reports from which little can be learned. For example, in the book *They Called it Pilot Error* there is a report of a student pilot, without a medical, forging a logbook, renting a light twin and, after a significant amount of drinking, taking friends on a flight to shoot birds. That they shot their own wing off is not surprising, and there is possibly little that can be learned from the incident by normal pilots although it raises the question of how a known alcoholic with no licence could rent an aircraft.

More usually, a qualified pilot *did* make the errors that caused the incident in the report. If you can't understand how the error could have been made, then perhaps you have not sufficiently thought through the steps that may have led up to the incident or imagined how the circumstances appeared to the pilot at the time: in the term used by David Woods and Richard Cook[3] you may not have uncovered the "second story". When a safety issue occurs, it is initially told as a "first story": an over-simplified account, distorted by the investigator's knowledge of the outcome of the event. The paper by Woods and Cook provides guidance on getting beyond the "first story" to the real, "second story" by removing the effects of hindsight, having a true understanding of the conditions under which the person making the error was operating and looking for systemic vulnerabilities and underlying patterns.

With the benefit of hindsight, you may be able to see *what* the pilot described in an incident report *should* have done but not *why* the pilot didn't do it.

Generally, as pilots we do not have the resources to carry out genuine investigations to find the true "second stories", but it can be useful to devise possible ones.

Exercise 1 *Consider the following incident report and try to imagine the circumstances that might have preceded the incident. An ultralight with two pilots on board was performing "low-flying manoeuvres" over a farmer's field when one of the wings struck a fence. Control of the aircraft was lost and it struck the ground.*

Possible answers to the exercises are given at the end of the chapter, starting on page 28.

In the dialogue given in section B.2 on page 342 the "first story" is very simple: the pilots were not concentrating on the landing and forgot to put the wheels down. The fact that the First Officer had been

[3] See *Nine Steps to Move Forward from Error,* published in "Cognition, Technology Work" in 2002.

the subject of a professionally damaging complaint by a previous Captain for insubordination forms part of the "second story".

1.4 Human Error

1.4.1 "Pilot Error" in Context

Many preventable accidents have a common factor, human error. Note that this does not imply that human error is the *cause* of accidents, just that it is one factor among many. It used to be the case that many accident investigations identified a human error as the cause and closed the investigation at that point, simply recording "pilot error".

More recent thinking is that, in most cases, the human error is not the cause of the accident but a symptom of an underlying problem that needs to be identified and addressed. Perhaps the earliest case of this approach was in 1943 when Alphonse Chapanis[4] was asked to investigate why pilots of P-47s, B-17s and B-25s often retracted the wheels instead of the flaps after landing. Chapanis immediately noticed that the wheel and flap controls in most cases were side-by-side and could easily be confused. He realised that the "pilot errors" were really cockpit design errors and he fixed the problem by attaching a rubber ring to the end of the wheel control and a small wedge to the flap control. The confusion disappeared. Dialogue 2 in appendix B.2 on page 342 gives another example of how a design error permitted the pilots to make an error.

Cohn's book, *They Called it Pilot Error* specifically looks beyond "pilot error" to find why the pilot made the error.

Pilots who have been involved in accidents generally know what went wrong and very often were aware of the possible hazards when making the error. In the interest of expediency, cost savings, self-gratification or other secondary factors, they took the wrong action.

Sidney Dekker summarises the difference between what he terms the "old" and "new" views of thinking about human error as follows:

- In the **old view,** a complex system would be fine were it not for the erratic behaviour of some unreliable people. Human errors cause accidents and failures come as unpleasant surprises: they are introduced into the system only through the inherent unreliability of people.

- In the **new view,** human error is not the cause of failure, it is the effect of deeper trouble. Human error is not random, it is systematically connected to features of people's tools, tasks and operating environment. In particular human error is not the conclusion of an investigation; it is the starting point.

The investigation into the gear/flap confusion represented the new view, whereas many of the techniques outlined in this chapter (Threat and Error Management, Reason's Model) effectively represent the old view. Dekker's argument is that by analysing from the old view, problems are "solved" by introducing new rules and regulations and this can often be counter-productive.

This book draws no conclusions about the efficacy of the old and new approaches: this whole area is subject to intense research.

1.4.2 Reason's Model

Generally, pilots and controllers do not deliberately behave in ways likely to cause accidents; they simply make errors. James Reason, professor of psychology at the University of Manchester, UK, has studied why this happens and has devised the "swiss cheese" model illustrated in figure 1.2 for categorising errors and providing means to prevent their recurrence. This model

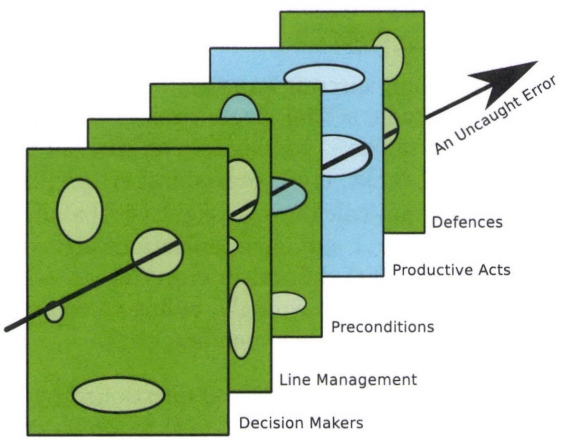

Figure 1.2: Reason's Model

consists of a number of layers, each of which should ideally either prevent the human from making an error or ensure that any error made does not cause an incident. Unfortunately each layer has holes and it is the alignment of these holes that leads to a pilot making an error and allows the error to lead to an aviation accident.

Starting from the front, the layers are:

Decision-Makers. Aviation is subject to many rules and regulations and this layer corresponds to the "big" decisions made by agencies such as governments and the directors or executives of the company operating the aircraft. In theory the

[4]Some sources attribute this investigation to Paul Fitts in 1947.

existence of the rules should prevent many incidents. A VFR pilot, for example, is not allowed to enter cloud, so no incidents should ever occur due to a VFR pilot becoming disoriented in Instrument Meteorological Conditions (IMC) and entering an unrecoverable spin or spiral dive. In practice, no set of rules can ever cover all eventualities, nor can any pilot's knowledge of them be complete. As illustrated in figure 1.2, the aviation rules and regulations have holes (omissions)—fallible decisions by the decision-makers.

Line Management. Any particular aviation enterprise, be it a commercial air service, flying school, flying club or group of pilots co-owning an aircraft, publishes its own rules. These, for example, often specify currency periods tighter than those set by Transport Canada (the "Decision-Maker") and are established in order to reduce the number of incidents caused by human error, but again they are bound to have holes (deficiencies). Standard Operating Procedures (SOPs) as described in section 1.8.2 on page 24 encapsulate the line management for an enterprise but they are certain to be incomplete.

Preconditions. When the causes of incidents are analysed, it is often found that preconditions were in place that made the human susceptible to making an error: perhaps the environment was noisy, or personal problems or fatigue were distracting the pilot from making correct decisions. While pilots and controllers generally try to reduce the number of such preconditions, they always exist and are the precursors of unsafe acts. In some cases a pilot has the intent of breaking a rule—another possible precondition.

Productive Acts. These can be considered the "pivot" of the model: the sequence of actions (or inactions) taken by the human that contains the unsafe act. Figure 1.3 (adapted from James Reason's book *Human Error*) provides a way of classifying the types of unsafe act. They can be divided into those acts that were unintended (a slip caused by lack of attention or a lapse caused by a faulty memory) and those that were intended (a mistake made because of lack of knowledge or a deliberate violation of a known rule). The word "sabotage" in figure 1.3 may be considered harsh but a VFR pilot, for example, who deliberately continues flight into deteriorating weather conditions in violation of the rules can be considered to have sabotaged the flight.

Defences. Even if an error *is* made, defences should be in place to "catch" it before an incident occurs. A copilot (or passenger) might notice a pilot straying from an assigned altitude, or an alarm might sound to indicate that the aircraft is very low without the wheels being down. Unfortunately, as with all of the other layers, defences are always inadequate, as illustrated by the holes in that layer in figure 1.2.

Reason argues that an incident occurs when the holes in each layer happen to align (as indicated by the arrow). When analysing an incident, it can be helpful to detect the holes in each layer that precipitated it.

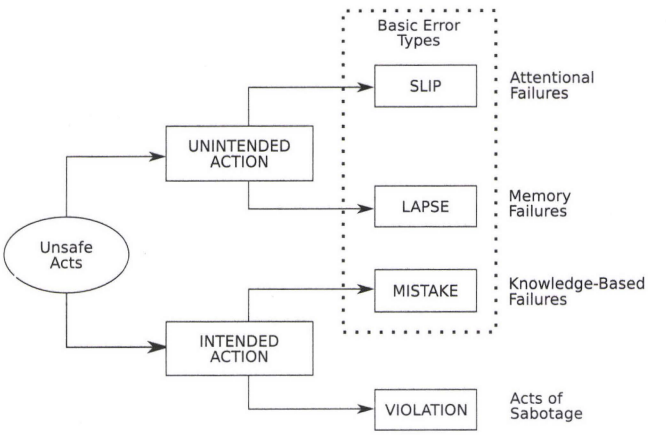

Figure 1.3: Classification of Unsafe Acts (James Reason)

Exercise 2 *Consider the following incident and identify "holes" in the various layers of Reason's model:* Jill forgot to lean the mixture on the long cross-country for her Commercial Pilot Licence, ran out of fuel and had to make a forced landing.

Anecdote 1 *On the first flying day after some weeks of bad weather, I decided (in accordance with the POH procedure for a cold weather start) to turn the propeller through several turns by hand before starting. I checked that the key was removed from the ignition. Unfortunately, the key, having become worn over the years, had been removed by a co-owner with the magnetos still live. I was hit by the propeller when the engine started and needed stitches in my hand.*

The productive act *here was clearly holding the propeller in such a way that, were the engine to start, I would be hit: an attentional failure. If I had been swinging the propeller to start the engine, I would have held it differently, but I assumed that, the key being out of the ignition, the magnetos were grounded. The*

major precondition *was that, following a period of weather-enforced grounding, this was to be my first cross-country flight for some time—I was impatient to get things ready to depart. Of course, the* defence *should have been the impossibility of removing the ignition key in other than the OFF position. This was a hole in the* line management *layer associated with my joint ownership: why had this not been reported and repaired? Another possible hole in the* line management *layer might be the training I had received: the key being out is the normal indication to ramp personnel that the propeller is dead. Even with the key correctly removed there is no guarantee that magnetos are grounded (perhaps the grounding wires have become detached since the last magneto grounding check) so perhaps students should be taught that all propellers should be treated as live, irrespective of the position of the ignition key.*

Immediately after the incident, I took actions to block the holes in the various layers of Reason's Model by having a new ignition lock installed and vowing to treat every propeller as though it were live.

1.4.3 The STAMP Model

Several criticisms can be levelled at Reason's model:

- It over-simplifies the interactions that occur to create the conditions for an incident.
- It treats the "system" and the "human actors" as different components. In fact, the humans (pilots, air traffic controllers, maintenance technicians, etc.) are not outside the system operating on it, they are an integral part of it.
- It is very linear: the various layers follow each other sequentially without significant feedback or interaction. In practice, feedback occurs between layers even as the incident unfolds: a *defence,* for example, might confuse a pilot and initiate an inappropriate *productive act.* An example is given in the appendix B.3 where a warning light is misinterpreted by the pilots who consequently take the wrong action.
- It can only be applied retrospectively—when an incident has already occurred the analysis can be used to identify and fill holes in the various layers. Would it not be better if the holes could be identified *before* the incident?
- It does not accommodate the incremental way in which many dangerous productive acts occur. A VFR-only pilot flies several times into deteriorating weather and survives (possibly with some good hangar stories to tell). This encourages her to penetrate increasingly worse weather until an incident occurs. An IFR pilot, possibly under the financial pressure of getting passengers to their destinations, dips a hundred feet below the minimum descent altitude (MDA) without a problem. Next time he ducks 200 feet under the MDA and his confidence builds until, one day, an incident occurs. In this case the pilot's error is not accidental: it is, in the vocabulary of figure 1.3, an act of sabotage.
- It encourages a "bring in a new regulation to block a hole" attitude. Changes to regulations made to address a small number of specific incidents tend to be piecemeal and ineffective: "hard cases make bad law".

These are valid criticisms and other researchers have produced more flexible and encompassing models; for example, Jens Rasmussen,[5] who dedicated his life to analysing human behaviour, applied control theory to modelling the complex feedback that occurs between the various layers: government, regulators, companies, management, etc.[6]

This work has been extended by Nancy Leveson and her team at the MIT in the USA where it has been termed *STAMP*: Systems-Theoretic Accident Model and Processes. STAMP is based in part on the observation that, in many dangerous situations, no component of the system actually failed; every component, including the humans who are part of the system, did what it was designed to do, but a dangerous situation still arose.

Unlike Reason's Model, STAMP can be applied both to analyse the causes of an accident after it has happened, and also to identify hazards and risks in a system before an accident has occurred.

The underlying artefact of STAMP is a control loop; a complex system consists of a hierarchy of control loops. At each level, a controller[7] receives inputs, typically from sensors, considers these in the light of its model of the system, and selects appropriate outputs; see figure 1.4.

For example, a VFR-only pilot who has entered cloud and is trying to control the aircraft, is a controller. The sensor data are coming from the instruments (airspeed increasing rapidly, aircraft in a turn, altitude being lost) and from the body's vestibular system (see

[5] The *Applied Ergonomics* Journal published an issue on Rasmussen's legacy in March 2017 with papers from a "who's who" of the safety world including Sidney Dekker and Nancy Leveson.

[6] See *Risk Management in a Dynamic Society: A Modelling Problem,* by Jens Rasmussen in Safety Science, Volume 27.

[7] The term "controller" in this paragraph does not mean an air-traffic controller, but rather an artefact that controls a process.

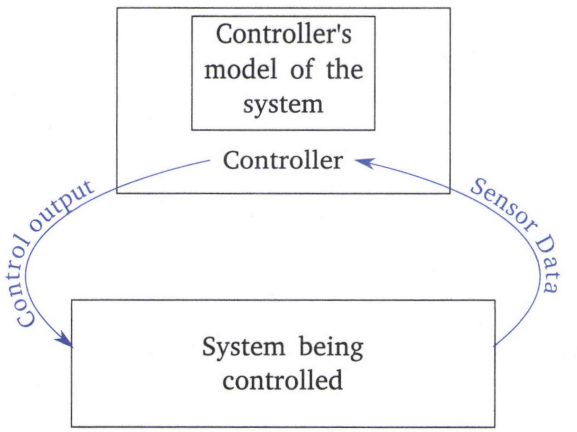

Figure 1.4: STAMP Control Loop

section 2.11.3 on page 45) indicating that the aircraft is in straight and level flight. The pilot is analysing this information against his mental "model" of the aircraft and deciding what action to take.

STAMP identifies a number of possibly dangerous conditions here: the input from the sensors (the instruments and body in this example) may be wrong, the mental model that the pilot has of the aircraft's behaviour may be wrong, or the aircraft might not correctly carry out the actions that the pilot takes. In the case of the VFR pilot in cloud all three of these may occur:

- the sensor input from the body's vestibular system is wrong: given those instrument readings, the aircraft is probably not in straight and level flight
- the pilot's mental model, built up over many hours of VFR flying, may be inadequate. In particular his mental model tells him that he should pull back on the control column to slow the aircraft.
- if the aircraft is in a spiral dive, then the pilot's action of pulling back on the control column may cause structural damage.

An example of a larger control loop occurs when the "controller" is an organisation such as Transport Canada. This controller has an internal model of how flight is taking place in Canada and is receiving inputs (accident reports, etc.), applying these to the model, and producing outputs (issues of the Aviation Safety Letter, modified regulations, more or fewer inspections, etc.).

The underlying concept of STAMP is that safety is not a function of the individual components of a system; it is an emergent property of the system itself. As Leveson has said, "you cannot confirm that a nuclear power station is safe by inspecting each of its components separately; you must analyse the whole as a system."

1.5 Managing Threats

1.5.1 A Personal Threat Model

Managing threats is largely a matter of identifying the risk associated with a particular situation and the actions that could be taken. Risk management and decision-making are interrelated—see section 1.6.

In the September 2008 issue of *IFR* magazine, Jeff Van West gave a challenging but useful way of considering risk. It has been observed that many pilots work hard to obtain a Private Pilot Licence and, after a few months, give up flying. This has been associated with risk and personal minima. The new pilot may initially set reasonable personal minima: perhaps no more than 10 knots of crosswind, at least a 3,000 ft ceiling, visibility of at least 5 miles, flights within 100 nm of the home field, etc. When a flight is being considered, if the winds are a little too strong or the visibility a little too low, then risk management determines that the flight should not be flown.

The problem is that these minima tend to shrink over time. Perhaps with a forecast 5 mile visibility the pilot encounters some patches of 3 mile visibility and gets concerned. She increases her visibility minimum to 6 miles. Perhaps with the 100 nm radius she gets lost once and reduces the radius to 50 nm. After a time she is restricted to flying only around the circuit on perfect days and, that being no fun, she gives up.

To balance the risk management associated with timidity or over-confidence, Van West proposes that each pilot have two sets of minima: an *envelope of comfort* and an *envelope of ability*.

The envelope of comfort contains those conditions within which you are totally comfortable. These might include 5 knots of crosswind on landing, a 3,000 ft ceiling, 5 miles visibility, eight hours of sleep the previous night, a 3,000 ft runway, a flight within the last 2 weeks, no more than 100 nm from the home airport and others.

The envelope of ability contains the conditions that you are capable of handling on your best day. These might include 10 knots of crosswind on landing, a 2,000 ft ceiling, 3 miles visibility, six hours of sleep the previous night, a 1,700 ft runway, a flight within the last 4 weeks, no more than 200 nm from the home airport. Rather than determining your personal envelope of ability yourself, an instructor might be asked.

The trick is then deliberately to fly on days when conditions are between the two envelopes: don't cancel a flight just because one parameter is outside the envelope of comfort; instead use it as a training opportunity. This can lead to an expansion rather than contraction of the envelope of comfort, and safer flying.

Of course, this technique works equally well not just for novice VFR pilots but for all pilots.

1.5.2 The Operating Environment

In addition to the "large", external threats of weather, operational pressure, etc., the operating environment within which a pilot works provides additional threats. Some of these are described in this section and all can be seen as *preconditions* in Reason's model. Many of these threats are of a physiological nature and are described in section 2.2 on page 33.

1.5.3 Situational Awareness

Loss of situational awareness can occur in both VFR and IFR flight and is a significant threat to a pilot. Such loss of awareness is a *precondition* for making an error in the terms of Reason's model.

Many aviation accidents, particularly controlled flight into terrain (CFIT), are caused by the crew losing situational awareness: the precise knowledge of where the aircraft is, what is ahead of it and what actions the pilot should be taking.

The causes of a loss of situational awareness include the following:

1. Ambiguity—contradictory information from two or more sources. This happens in the general aviation cockpit when, for example, the VOR receiver and GPS disagree.

Anecdote 2 *I was once navigating to the Mirabel VOR (YMX) just north of Montréal and getting differing information from my VOR receiver and GPS. Situational awareness was lost until I realised that I had entered the identifier for the Mirabel airport (CYMX) into the GPS rather than the identifier for the VOR. Often ambiguity of this sort is not so easy to detect and correct.*

2. Fixation—focusing on one thing to the exclusion of others. This is often caused by fatigue.

Anecdote 3 *Fixation has also affected me when flying to Mirabel airport. I spotted what appeared to be an airport some distance ahead of the aircraft and fixated on it. It was only after some minutes of fixation (and loss of situational awareness) that I glanced out at the 2 o'clock position to see Mirabel airport just a couple of miles away.*

3. Confusion—uncertainty or bafflement about a situation (often accompanied by anxiety or psychological discomfort). This often happens after some form of system failure.

Loss of situational awareness is obviously most important in IFR flight and, in particular, during an IFR arrival and approach.

Anecdote 4 *I was under the hood in VFR conditions with a safety pilot in the right seat, flying to Ottawa International Airport to practise ILS approaches. The safety pilot had never flown to Ottawa Airport before and was not experienced in IFR approaches. She could therefore not help in the amazing loss of situational awareness that resulted from the controller vectoring me for the approach on runway 07 when I was expecting, and had set up the radios for, the approach to runway 32. In retrospect I should have known that the vectors I was being given made no sense for runway 32 but my loss of situational awareness was complete—I was acting as an autopilot flying the given headings, descending to the given altitudes without any thought of whether they made sense situationally or not.*

Various reports (e.g., *Pilot Situation Awareness Training in General Aviation*[8] by Mica R. Endsley and Daniel J. Garland) have been written investigating the changes needed in the training environments of general aviation pilots to cover situational awareness better. One particularly important topic is the recommendation to know the *precise* significance of warning indications—e.g., in a Cessna 172M, *precisely* what does an over-voltage alarm mean? The conclusion of Endsley's and Garland's paper says:[9]

> Pilots with high levels of SA actively seek out critical information, making them quicker to notice trends and react to events. These pilots are also good at checking the validity of their own situational assessments, either with more information or others. This is effective in dealing with false expectations and incorrect mental models. Other researchers have also suggested a "Devil's Advocate" strategy where pilots are encouraged to challenge their own interpretations of situations.

[8] From Proceedings of 14th Triennial Congress of the International Ergonomics Association and the 44th Annual Meeting of the Human Factors and Ergonomics Society – 2000

[9] Note that "SA" means situational awareness.

1.5.4 Stress

A certain amount of stress is beneficial because it counterbalances boredom and complacency. However, too much stress causes fatigue and, in Reason's model (figure 1.2), is a *precondition* for making an error.

The cockpits of most light aircraft are noisy, they vibrate and are often very hot or very cold. Physical preconditions of stress therefore already exist in the cockpit and, in addition, pilots sometimes bring psychological stress from their everyday life.

As with fatigue, psychological stress exists in two forms:

1. **Acute stress.** This is stress caused by the current conditions. Good preparation can reduce the probability of acute stress occurring. For example, reviewing approach plates and noting some of the waypoint names likely to be used by controllers while you are in the more relaxed cruise portion of a flight can help avoid sudden stress during the arrival at a destination. If acute stress does arise, then avoid hyperventilation (see page 35) by taking regular and slow breaths.

2. **Chronic stress.** This is stress caused by a long buildup of stressful conditions, mostly outside the cockpit. This cannot be remedied in the cockpit—it must be accomplished by changes in lifestyle.

All types of stress, whether physical or psychological, cause fatigue (see section 2.8 on page 42) and some books (e.g., *Human Factors for General Aviation* by Trollip and Jensen and *Human Factors in the Training of Pilots* by Koonce) contain lists that a pilot can use to check his or her current level of stress.

Anecdote 5 *I like to work from effect rather than from cause and have a personal rule that says that if I make three mistakes between arriving at the airport and taking off, then I cancel the flight. Every pilot has a personal routine for preflight inspection, but during mine, for example, noticing when arriving at the right fuel tank during the pre-flight checks, that the fuel cup is not on the passenger seat because I forgot to drain fuel from the left tank, would count as one mistake. Finding that the tail tie-down had not been removed before the start of the checks would count as a second. Each of these is easily remedied, but making the mistakes indicates that I am under stress. Anyone can make one or even two mistakes but three indicates that I am under too much stress. Every pilot should have a rigid rule for assessing stress in the same way that they have personal limits for crosswinds on landing, etc.*

1.5.5 Handling Workload

Everyone has a maximum level at which they can process information. When there are significant distractions, this level can reduce. High workload in the cockpit is, in terms of Reason's Model, a *precondition* for an incident.

Anecdote 6 *I was once at a demonstration given by Dr Sandra West where she had a "volunteer" play with a yo-yo. Once the volunteer had settled in and the yo-yo was moving easily up and down, she turned on a nearby radio very loudly. The volunteer found it harder to keep the yo-yo bouncing. She then passed him a portable radio and started asking him questions, as a controller might; his yo-yo came to a stop.*

In his book *Fate is the Hunter*, Ernest Gann tells the story of Captain Ross repeatedly lighting matches and holding them under Gann's nose to distract him while he was trying to make a difficult IFR approach into Newark. Four years later, with his cockpit full of smoke from a fire in the cargo hold, Gann writes *"... as if he had emerged from the smoke, I saw Ross. And he was holding lighted matches in front of my nose as we descended into Newark. And I saw his sardonic smile and heard him say again 'Steady'. "*

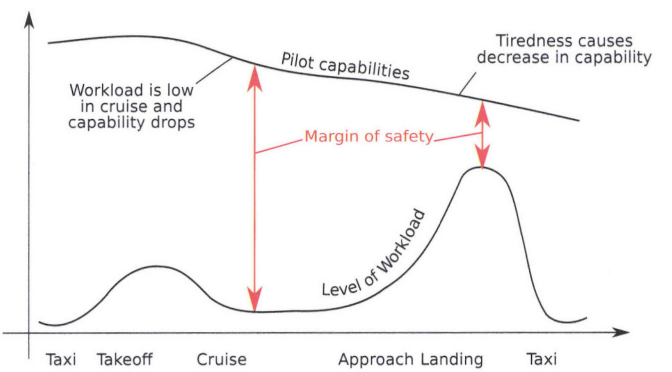

Figure 1.5: Workload and the Margin of Safety

In both of these cases a pilot had to keep his attention on the important issues, and process the information from those issues, in the face of significant distractions. It is often said (by candidates) that flight tests are unnatural because so much activity is concentrated into such a short time. In an IFR flight test the candidate may be required to enter a hold within minutes of departing and then make several approaches without a break. This is unnatural for normal IFR flying and significantly increases the normal IFR workload. How the pilot reacts to that workload is part of the test.

Figure 1.5 illustrates another issue related to workload and flight-tests. Landing an aircraft, particularly in a strong crosswind or in low IFR conditions, is a high-workload activity. If a late runway change is added to the mix, requiring an approach GPS to be reprogrammed quickly, the workload increases. Unfortunately, landing happens at the end of a flight when the pilot is most fatigued and when, in general aviation flights, passengers might be at their most distracting. The descending level of pilot capability must still be adequate at the end of a flight to handle the extra workload of arrival and approach. This fatigue can be artificially replicated during a good flight test by the number of activities the candidate has to perform.

The relationship between workload and performance is complex. At low workload, such as during cruise, performance is actually poor, and the pilot's ability to react to an emergency is low. The standard of performance increases as workload increases up to an optimum level. At higher workload (overload), performance again falls off. Pilots need to place themselves in safe situations (e.g., simulators with an instructor) periodically so that they can explore these different workloads and ensure that, when necessary, they can identify and give their attention to the essential aspects of a situation, disregarding non-essential input.

1.5.6 Visual Scanning Techniques

When flying in VMC, it is the duty of all pilots, whether flying on a VFR or an IFR flight plan, to see and avoid other aircraft. Remember that ATC only provides IFR aircraft with separation from other IFR aircraft—not from VFR ones.

To understand how, where and why mid-air collisions occur, a study entitled *Review of Midair Collisions Involving General Aviation Aircraft in Australia between 1961 and 2003*[10] provides an analysis: see figure 1.6.

This study confirms the results of other studies performed in France, the USA and elsewhere. The general findings are:

- Mid-air collisions occur most often in the circuit area around airports. For example, excluding deliberately dangerous flying, 77% of the accidents in the Australian study happened in the circuit and 94% within 5nm of an airport.
- Within the circuit, most accidents occur on final approach. In the Australian study, almost one third of the accidents in the circuit occurred on final approach.

[10] Available at `http://www.atsb.gov.au/publications/2004/pdf/Review_of_midair_col.pdf`.

Position	Fraction of Collisions
In the Circuit	
Upwind	2.7%
Crosswind	5.4%
Downwind	16.2%
Turn to Base	2.7%
Base	0%
Turn to Final	5.4%
Final	32.5%
Out of the Circuit	
Within 5nm of airport	13.5%
More than 5nm from airport	5.4%
Dangerous Flying	
Deliberately close flying	16.2%

Figure 1.6: Mid-Air Collisions in Australia 1961-2003

- Most of the accidents in the circuit happened when one pilot did not follow the correct circuit procedures at the airport.
- Almost all mid-air collisions occur during the day in good VMC.
- Almost all mid-air collisions occur between aircraft converging while travelling within 30° of the same direction. Head-on collisions are rare.

When viewing the numbers in figure 1.6 from the point of view of human factors, it is salutary to consider the accidents caused by "Deliberately Close Flying". These include several attempts at privately-agreed upon formation flying and the following:

- A CA28C that collided with a Cessna C172 when flying close to warn of turbulence. At least one of the aircraft was not equipped with a radio.
- A Piper PA-31 that collided with a Cessna C210 travelling in the same direction when attempting to scare the pilot (!).

The statistics given above emphasise the need to be very aware of the position of other traffic in the circuit, particularly when the circuit is non-standard (e.g., right-hand or joining straight into the downwind leg). The statistics also emphasise the need to scan not only straight ahead, but also to the sides to locate converging

aircraft. It is recommended that you scan 60° either side of straight ahead and 10° above and below the flight-path.

From a physiological point of view, scanning is not effective when the eye is moving, because the image is blurred. To be effective, the eye must be still and concentrated on one area. Given the large volume of space to be scanned, a pilot needs to have a habitual scan pattern and apply it.

There are other, secondary, practices available to avoid mid-air collisions:

- Clean your windows regularly. A bug on the windscreen is the same size as an oncoming light aircraft 30 seconds from collision. A small aircraft one nautical mile away looks, from wingtip to wingtip, the same size as a bottle cap five metres away.
- Make good use of ATC's "conflict resolution" service. If you are being provided with flight following and ATC points out traffic that you cannot see and that you believe might be a threat, then ask for "conflict resolution". ATC will provide you with a vector to avoid the other traffic. Remember, however, that even when you have flight following, the controller is under no obligation to notice or inform you of conflicting traffic—it is a service provided only "if workload permits".
- If you are in a light aircraft, then use your passengers. Explain that they will often see another aircraft before you do, and that they should indicate its position to you.
- On final approach in a high-wing aircraft, always consider the possibility of a low-wing aircraft flying above you. On final approach in a low-wing aircraft, always consider the possibility that there is a high-wing aircraft below you.
- Use your radio. At an uncontrolled aerodrome, announcing the turn from downwind to base is not required, but worth making on the principle that, if the frequency is clear, one extra call doesn't matter and, if the frequency is congested, there must be many aircraft in the circuit and announcing the turn is useful. Another tip is to announce that you are turning *onto* downwind, base or final, rather than that you are *established* on downwind, base or final. If someone hears your call and looks for you, a banking aircraft is easier to spot than one in straight and level flight.

  In areas where there are several aerodromes within radio range on the same traffic frequency it is useful to say the name of the aerodrome both at the beginning and the end of the transmission. For example, "Rockcliffe Traffic, Papa Tango November turning right base, runway 27, Rockcliffe". This gives other pilots a second chance to hear who the intended recipients are.

1.6 Pilot Decision-Making

1.6.1 Decision-Making

As pilots, our decisions begin with flight planning (whether to depart, how much fuel to carry, the route, the alternate route, weather conditions, etc.) and continue throughout the flight (speed, altitude, weather avoidance, etc.). In each case, once a threat or potential threat has been identified or an error has been recognised, a decision must be made: what action (if any) should be taken? The decision itself may turn out to be incorrect. It is important not to assume that any decision is final—the threat must be continually monitored until it disappears.

It is estimated that a pilot makes a decision on average every 30 seconds during a flight. In many cases a poor decision leads to the Productive Act in Reason's Model (figure 1.2).

There are two parts to decision-making; in the book *Human Factors for General Aviation* (see above) they are referred to as *Headwork* and *Attitude*:

- *Headwork* means recognising the threat or error that makes a decision necessary, collecting the necessary information, identifying possible options and assessing the risk and benefit associated with each.
- *Attitude* is determined by the personality of the person making the decision, whether he or she is cautious, headstrong, keen to take risks or trying to impress a friend. The right attitude increases the chances of making a safe decision; having the wrong attitude is dangerous.

1.6.2 Benner's DECIDE Model

In 1975 Ludwig Benner wrote a paper[11] entitled *D.E.C.I.D.E. In Hazardous Materials Emergencies* in which he introduced a model for structuring a decision process. This identified six steps:

1. *Detect* the presence of hazardous materials. In the aviation world this is the equivalent of detecting a threat or error that requires a decision.
2. *Estimate* Likely Harm Without Intervention. This can be thought of as determining whether the

[11] Available at `http://ludwigbenner.org/HMdocs/DECIDE.html`

situation is *critical* (I am in a spiral dive in cloud), *important* (I am lost) or *trivial* (should I fly to the north or south of the small cloud ahead of me?).

3. *Choose* Response Objectives. Many students misunderstand this step. It does not mean selecting possible actions: instead it means making a clear statement of what outcome would be desirable. Possibilities might be: "I want to be safely on the ground", "I want to know my position", "I want to remain in safe flight". Part of this step might be to determine the priorities of what should, and what need not, be saved: *"I want to be safely on the ground with my passengers even if this means deploying the ballistic parachute which may destroy my aircraft".*

4. *Identify* Action Options. This step means mentally listing possible actions that could be taken and assessing the risks and likely outcomes of each.

5. *Do* Best Option. This refers to the productive act of executing the option that you believe to be best.

6. *Evaluate* Progress. Once the action has been taken, the results of taking the action need to be assessed to ensure that the action itself was not an error: did it give the results you expected? If not, it may be necessary to restart the DECIDE process.

Benner's process is known by the initial letters of the six steps as the DECIDE model. The first four steps in the DECIDE process are part of the "headwork" involved in decision-making; pilots will differ only in the imagination they apply to step 4. However, the attitude of the person making the decision is likely to affect steps 5 and 6 significantly.

Many decisions in flight have to be made so quickly that it is impossible to carry out a formal process of analysis in this way—see exercise 3 below. Because of this, a good pilot will imagine "what if?" scenarios throughout flight: what would I do if the engine were to fail now? what shall I do if the cloud layer continues to get lower? In the former situation, you should always have a landing spot in mind—in VMC this might be a road or field, in IMC the nearest aerodrome. In the latter you should determine a strict altitude limit at which a clear decision must be made. This covers the first few steps of the DECIDE model informally and reduces the time needed to make a decision should the circumstances actually arise.

Exercise 3 *You are flying a Cessna 172 VFR at 8,500 ft ASL past Syracuse (New York, USA) airport and have flight following from Syracuse Approach. You are in VFR conditions, but the clouds are building rapidly around you. You realise that you will need to descend quite quickly to remain VFR and inform Syracuse Approach that you are starting a descent to remain VFR. Approach immediately responds with "Canadian Papa Tango November, HOLD ALTITUDE" with alarm in his voice. What action do you take?*

1.6.3 The Q850 Process

As an alternative to Benner's DECIDE model, when making decisions in an organisational rather than flying setting, Transport Canada has published a document entitled *TP 13095 Risk Management and Decision-Making in Civil Aviation* which is freely available from the Transport Canada website. That document applies the so-called "Q850" decision-making process developed by the Canadian Standards Association (CSA) to the aviation environment.

Unlike Benner's DECIDE model, Q850 is applied to making decisions as part of a process on the ground rather than in real-time in an aircraft, but there are significant similarities.

Q850 itself has 6 steps in the decision-making and risk-mitigating process; Transport Canada has split one step into two, providing a 7 step process—see figure 1.7. The steps are as follows:

1. *Initiate Process.* This is similar to Banner's "Detect Change" and during this step the risk is identified and the need to make a decision is recognised, the problem is defined and the people who will be affected by the decision (the "stakeholders") are identified.

2. *Perform Preliminary Analysis.* This step, equivalent in many respects to Benner's "Estimate its Significance", includes the creation of risk scenarios ("what would happen if X?") and the initial analysis of potential risk—is immediate action required?

3. *Estimate Risk.* The probability and consequences of the various risk scenarios are estimated and discussed with the stakeholders.

4. *Evaluate the Risk Activity.* This step follows from the previous one and produces a more in-depth evaluation of the risk involved and the benefits and costs of the activity with which the risk is associated. Stakeholders are asked about whether or not the risk would be acceptable to them if it could be mitigated.

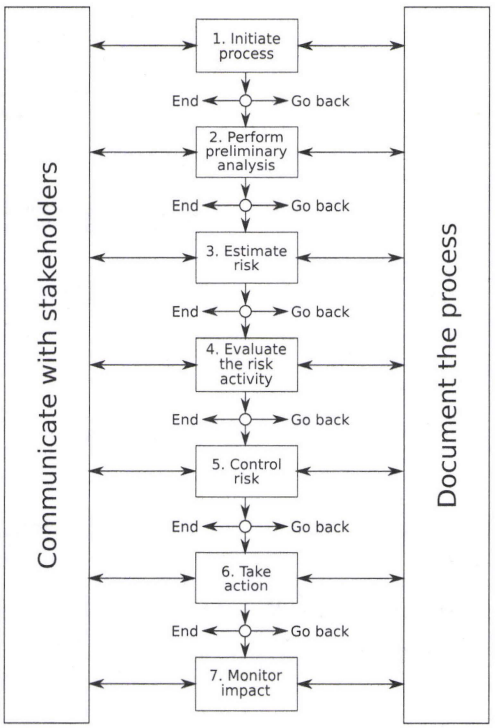

Figure 1.7: The Q850 Process (As modified by Transport Canada)

5. *Control Risk.* As in Benner's "Identify Possible Actions", various options for mitigating the risk are considered. Stakeholders are made aware of the decision and given the opportunity to comment.

6. *Take Action.* This is Benner's "Do the Best Option": the decision is implemented and the strategy for communicating it is put into play.

7. *Monitor Impact.* As in Benner's "Evaluate the Effect", this step monitors the effectiveness of the decision. Monitoring is essential because it provides an opportunity to identify new risks, or assess the impact of changes in known risks.

As shown in figure 1.7, after each step the opportunity arises for previous steps to be revisited in the light of the new information or for the whole process to be stopped (if, for example, it is found that the cost of mitigating the risk is too high relative to the impact of the risk).

Exercise 4 *You own a one-sixth share in a Mooney and the agreement that your group has in place does not mention any currency requirements for members flying. One of the partners, Fred, believes that flying the aircraft after a long absence from flying is a risk and believes that a new bylaw should be added to the group's agreement to cover this. How might Transport Canada's 7-step process be applied to this situation?*

1.6.4 Factors In Decision-Making

Training

It cannot be denied that good training can provide the information required to make good decisions. However, there are examples where apparently good training might have led to incorrect decisions and accidents. One such example is Colgan Air Flight 3407 which crashed on approach to Buffalo, USA on 12th February 2009. The Dash-8 aircraft was approaching through potential icing conditions when the stick-shaker indicated that it was approaching a stall. Rather than pushing the nose down, the pilots pulled the nose up. It is not known why they did this, but the USA's National Transportation Safety Board report states:

> The NTSB evaluated whether the captain responded incorrectly to the stick shaker onset because he was applying corrective techniques that would have been more appropriate for a tailplane stall event. The captain (as well as the first officer) had seen, during initial and recurrent ground school, a NASA-produced icing video that discussed tailplane stalls and recovery techniques. The video indicated that tailplane stalls were most likely to occur with regional and corporate turboprop airplanes and during flight in icing conditions with ice present on the horizontal stabilizer. ... The tailplane stall recovery procedure presented in the video called for pulling back on the control column and reducing flaps, which the accident flight crew did.

It is possible that the emphasis during training on the NASA video led to an incorrect decision—the tailplane had not stalled.

Hazardous Attitudes

As noted above, one substantial factor that affects decision-making is the attitude of the person making the decision. This involves at least the last two of the steps in the DECIDE process.

The Federal Aviation Authority of the USA issued an advisory circular in 1991 with the title *Aeronautical Decision Making*[12] This identifies five hazardous attitudes:

1. **Anti-Authority** (don't tell me!). This attitude is found in people who do not like anyone telling them what to do. In a sense they are saying "no one can tell me what to do". They may be resentful of

[12] Document AC 60-22.

getting advice or may regard rules, regulations and procedures as silly or unnecessary.[13]

2. **Impulsive** (do something quickly!) is the attitude of people who feel the need to react to a problem by doing something immediately. They do not stop to think about what they are about to do, they often do not select the best option, instead doing the first thing that comes to mind.

3. **Invulnerable** (it won't happen to me). Many people feel that accidents happen to others, but never to them. Although they *know* accidents can happen to anyone, they never really *believe* that they will ever be personally involved. Pilots who think this way are likely to take risks.

4. **Macho** (I can do it). Pilots who are always trying to prove that they are better than anyone else are thinking, "I'll show them". Pilots with this type of attitude will try to prove themselves by taking risks in order to impress others. While this pattern is thought to be a male characteristic, women are also prone to it.

5. **Resigned** (what's the point?). Pilots with low self-esteem do not see themselves as being able to make a great deal of difference to what happens to them. When things go well, the pilot is apt to think "that's good luck". When things go badly, the pilot may feel that "someone's out to get me", or attribute it to bad luck. For better or worse, these pilots will leave action to others. Sometimes such pilots will even go along with unreasonable requests just to be a "nice guy".

Exercise 5 *You normally lower flaps on base. While you are on downwind, the tower suddenly changes the active runway and, distracted, you forget to lower flaps. On short final you find yourself low with a high sink rate. Glancing down, you realise that you forgot to extend the flaps. For each of the following actions, describe the hazardous attitude of the pilot.*

1. *You feel that nothing is going to happen because you have made intentional no-flap landings before.*
2. *You laugh and think, "Boy, this low approach will impress people on the ground."*
3. *You are not surprised because you think that using a checklist is a stupid requirement anyway.*
4. *You immediately grab the flap handle and add full flaps.*
5. *You think that it all depends on whether you get an updraft or downdraft now.*

[13] Remember however that it is always your prerogative, indeed your duty, to question authority if you feel it is in error.

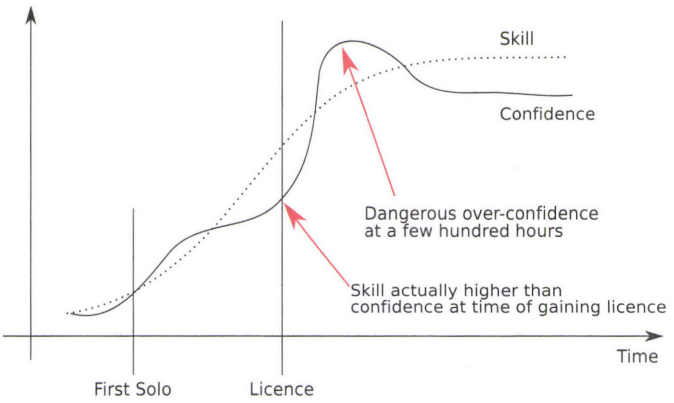

Figure 1.8: Piloting Skills and Confidence

Exercise 6 *For a caricature of five VFR pilots, each with one of the hazardous attitudes listed above, describe what the pilot's approach might be to the problem discussed in example 3 on page 18.*

Every pilot has some degree of every one of the hazardous attitudes but, in most cases, one dominates. Document AC 60-22 has a short quiz that you can use to determine your dominant attitude, but it is probably quicker to ask your partner or a trusted friend.

At different times in a flying career the levels of the various hazardous attitudes are also likely to change. As figure 1.8 indicates, many pilots experience a significant increase in confidence after a few hundred hours of flying. This may outstrip their skill at this time and increase macho feelings and a sense of invulnerability.

The antidotes to the hazardous attitudes are straightforward: see figure 1.9.

Anecdote 7 *I have found the antidote to invulnerability in figure 1.9 particularly useful. Shortly after getting my Private Pilot Licence, I needed to fly back from Kingston, Ontario to Ottawa Rockcliffe on a Sunday evening with my wife and son. The trip was "necessary" because I had an important meeting in Ottawa on Monday morning. A line of thunderstorms was clearly visible to the north of Kingston and flight services confirmed that the line was continuous from the north west to south east. After several calls to flight*

Hazardous Attitude	Antidote
Anti-Authority	Follow the rules. They have probably been written for a good reason and are probably right.
Impulsive	Slow down. Think before acting.
Invulnerable	Realise that it could happen to you and think what it will look like in the incident report.
Macho	Realise that taking chances is foolish.
Resigned	Realise that, as a pilot, you are not helpless and your actions can make a difference.

Figure 1.9: Antidotes to Hazardous Attitudes

services, I thought I spotted a small gap in the thunderstorms, bundled my wife and son into the aircraft and headed north. Soon after taking off, a stroke of lightning appeared immediately in front of us and I thought of the incident report: "In spite of numerous weather briefings, a low-time, private pilot took off and flew directly towards a line of thunderstorms... ". I turned around and returned to Kingston where the thunderstorms hit violently an hour later. The journey was resumed early the following morning. It was the thought of the incident report that made me turn around—this was the sort of incident report over which I would have shaken my head and said, "How could anyone have been that stupid?".

Exercise 7 *What hazardous attitudes were demonstrated in the decision, described in anecdote 7, to take off and fly towards the line of thunderstorms?*

Anecdote 8 *Although the decision I made in anecdote 7 was bad, it was not the worst decision I have ever made. Once, when returning from a "$100 dollar hamburger" lunch at an airport some 40 minutes flying from my home base, I noticed a pronounced mechanical banging noise towards the tail of my aircraft during the runup. I ignored it and taxied for takeoff. As I started the takeoff roll, the banging got worse but, although I had 4,000 ft of runway ahead of me, I "decided" to continue and climb to cruising altitude. Actually, of course, I made no such decision—it would be more accurate to say that I allowed the takeoff to continue.*

Once I was in cruise I asked another pilot to come alongside me to see whether the cause was apparent. It was: a strap from the engine cover on the back seat was hanging out of the door and its plastic buckle was hitting the side of the fuselage.

This incident didn't occur when I was a 100 hour private pilot but when I was a 2,000 hour commercial pilot who had been teaching Human Factors and Pilot Decision-Making for many years.

Again, it may be instructive to determine what hazardous attitudes I demonstrated.

The Sunk Cost Fallacy

The *sunk cost fallacy* is normally applied to financial investments, but it's also applicable to pilot decision-making. In its simplest form, this fallacy says that because some resources (often money or time) have already been sunk into an investment, we are likely to invest further. This happens because humans are averse to "wasting" resources. This is generally a fallacy—the wisdom of further investment at any time needs to be weighed based on the current situation, not on previous investments.

In aviation, it is generally believed that the decisions pilots make tend to be affected by the amount of effort that they have already invested in a flight. However, in a report entitled *Continued VFR into IMC: An Empirical Investigation of the Possible Causes* published in November 1999, David O'Hare and Douglas Owen formally tested the "sunk cost" hypothesis by making pilots fly a simulated cross-country flight during which they encountered adverse weather either early or late in the flight. The prediction was that pilots who encountered the bad weather late in the flight would be more likely to continue because of the greater investment of time already spent *en route*. However, the results of the study failed to support the sunk-cost hypothesis because most pilots in both conditions chose to divert the flight.

It is unclear whether the experiment was flawed (the conditions being too clearly simulated) or whether most pilots avoid the sunk-cost fallacy. Further experiments by O'Hare, Owen and others have indicated that the amount of time that pilots take to choose to divert a

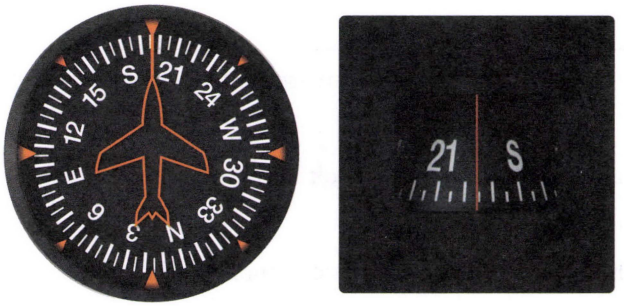

Figure 1.10: The Heading Indicator and Compass

VFR flight that is heading towards IMC conditions is a better indication of whether an accident will occur.

The report *Pilots' Decisions to Continue Visual Flight Rules (VFR) Flight into Adverse Weather: Effects of Distance Travelled and Flight Experience* by Douglas A. Wiegmann, Juliana Goh and David O'Hare takes the experimental work further and tests other hypotheses about why VFR pilots fly into deteriorating weather.

1.7 The Pilot & Equipment

1.7.1 Controls & Displays

The standard cockpit in general aviation aircraft contains a number of instruments presenting similar information in different ways. Consider figure 1.10 which shows two instruments that provide heading information. Given an urgent instruction from ATC to "turn south now!" when looking at the heading indicator on the left of figure 1.10 the natural reaction would be to turn left. The reaction of many pilots to the same instruction while they happened to be looking at the compass on the right of figure 1.10 would be to turn right. In fact both instruments are displaying the same information (a heading of 196°) and a 14° left turn is appropriate in each case. It is possible to buy vertically-mounted magnetic compasses that display the heading information with the same orientation as the heading indicator but, in general-aviation aircraft, these are relatively rare.

Another pair of instruments that present overlapping information differently are the attitude indicator (stationary aircraft, moving horizon) and the turn co-ordinator (stationary horizon, moving aircraft). When a pilot flying in IMC finds that the attitude indicator has failed, she has to switch immediately to the turn co-ordinator and interpret the information differently. For this reason, some pilots install supplementary, electrically-powered attitude indicators in the spot normally reserved for the turn co-ordinator for practical use in flight and tiny turn co-ordinators to remain legal.

These confusing displays are, in Reason's terms, *preconditions* for errors to be made but their origin is obviously in the *decision-maker* layer—pilots generally have to fly with the instruments they are given.

Other instruments can be confusing in themselves: altimeters are frequently misread by 1,000 ft and sometimes by 10,000 ft—see, for example, anecdote 28 on page 208.

The introduction of GPS equipment into the cockpit has led to more issues of interpretation as, unlike more traditional navigation equipment such as VOR receivers, each GPS unit has a different user interface.

The advent of glass cockpits gave the aviation industry the opportunity to rationalise the display of information but this has itself led to errors of interpretation. For example, the British Midland 737-400 crash on 8th January 1988 was caused by the pilots misreading the Engine Monitoring and Control System and shutting down the wrong engine following a fan blade failure.

Another example of poor information presentation in a glass cockpit caused the Airbus 320 crash at Strasbourg on 20th January 1992. To complete a non-precision approach, the pilots calculated that a descent angle of 3.2° was required to reach the minimum descent altitude while keeping the aircraft clear of the mountains. To program this into the flight director,[14] the pilots had to turn a particular knob until "3.2" appeared on the display and then pull it out. But this same knob served two functions. Depending on whether a nearby button had been pushed or not, this knob would command the aircraft to descend either in degrees or at a particular vertical speed. The pilots thought they had commanded the plane to descend at an angle of 3.2° but had actually instructed it to descend at 3,200 ft per minute—a decent that took them directly into the mountains. On the display, the only difference between 3.2° and 3,200 ft/min was in a decimal point: the display read "3.2" or "32" depending on which mode was set.

The section *Markings* on page 205 describes another example of poor instrument design.

1.7.2 Errors in the Interpretation & Use of Maps/Charts

Maps, charts, approach plates and other situational information used by pilots are created by humans and often contain errors. On the Toronto VNC, for example, several large towers were drawn on the wrong side of the 401 highway between Ottawa and Montréal for many years. For some months the NDB that formed part of one of the instrument approaches into Carp, Ontario, didn't exist—it had been renamed and its frequency and

[14] See page 299 for a description of flight directors

identification changed but the approach plate had not been updated.

Even when the map is correct, it may be out of date (see section 6.3.3 on page 122 for the means of determining the current version of those maps and charts without expiry dates). Using an out-of-date map for anything other than the basic positions of large ground features and airports can be very dangerous. Radio frequencies might have changed, Class F airspace may have been introduced and, more importantly, minimum obstacle clearance altitudes might have increased.

The symbology on maps and charts can be confusing and sometimes inappropriate. For example, consider the aerodrome information included on a standard VNC. This includes the not-very-useful information of the longest night-time runway (best found from the CFS) but does not contain the most useful piece of information in these days of GPS navigation—the ICAO identifier of the aerodrome (this useful piece of information *is* found on the USA equivalent of the VNC, the sectional chart). Many GPSs have a "nearest aerodromes" feature but consider a pilot with a simple GPS without this feature needing to reach a nearby airport in an emergency. Seeing the aerodrome on the map he or she needs to enter its identifier into the GPS. This has to be extracted from the CFS, wasting potentially valuable time.

The issue of confusing symbology has been apparent with the increasing use of electronic navigation displays in the cockpit. There are no clearly-defined standards for how navigational information should be displayed on these types of display. Various groups are working to produce standards including:

- ICAO that has produced documents entitled *Aeronautical Charts Standards and Recommended Practices* (SARPS) and *Minimum Operational Performance Standards for the Depiction of Navigational Information on Electronic Maps.*
- the Society of Automotive Engineers (SAE) that has developed an Aerospace Recommended Practice (ARP) for electronic aeronautical symbols.

The possibility for confusion is rife. Consider, for example, the symbol for a DME ground station as illustrated in figure 1.11.

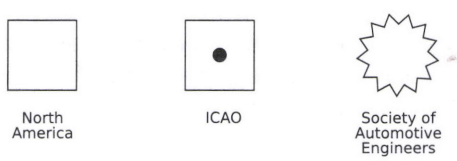

Figure 1.11: Glass Cockpit DME Symbols

In designing electronic navigation displays, the manufacturers have to take into account not only the ease of reading the symbols on the display but also the possibility of a pilot wanting to confirm something on a printed map and having to switch rapidly between the electronic and paper maps.

There are many papers published pointing out the problems associated with this transition to electronic navigation displays. The interested reader might like to start with *Issues in Symbol Design for Electronic Displays of Navigation Information* by Michelle Yeh and Divya Chandra which has a short but useful bibliography.[15]

All of these issues lie within the *decision-makers* layer of Reason's model.

1.7.3 Automation & Complacency

In many aircraft, the pilot's role has changed over the years from flying the aircraft to monitoring the automated systems that fly it. This leads to several issues that have been identified by various researchers including Mark Scerbo at Old Dominion University.

- Automation is typically introduced to improve efficiency and safety by reducing the cognitive strain on pilots. However, this often leads to under-stimulation. For example, automated systems usefully reduce cognitive load on pilots during high-demand portions of a flight, such as takeoff and landing, but they leave pilots with little to do during the main part of the flight. On a long-haul flight the tedium can be significant. As Mark Scerbo has said, "The human mind didn't evolve to be unstimulated and if it is, it provides its own stimulation—daydreaming". Andrew Carhart, *et al* state in a 1999 paper entitled *"A Study of Critical Systems in Military and Commerce"*,

  > "... the plane is so automated that the pilot is for the most part reduced to the role of system manager, programming in flight paths and such, while the computer actually flies the plane. With little to do, pilots become complacent."

  As a consequence, when an automated system fails, pilots are often slow to notice and react.

- Automated systems can also lead to a decline in manual skills. Without practice, people lose their ability to react effectively when an emergency arises. This has led to the concept of "adaptive automation", the idea that an ideal automated system changes its functioning in response to how

[15] Published at the 23rd Digital Avionics Systems Conference in Salt Lake City, USA, 2004.

> the human is working. The system takes on tasks when the pilot is overloaded and gives them back when the pilot is under-loaded, keeping the level of pilot involvement at a stable level and allowing them to keep practising their skills.

Issue 507 of NASA's *Callback*[16] contains reports of a number of incidents where pilots have entered commands into a flight director and become distracted by other activities before realising that the commands were not being carried out.

In her paper, *Ironies of Automation*, Lisanne Bainbridge made the astute observation that "By taking away the easy parts of his task, automation can make the difficult parts of the human operator's task more difficult." This 1987 observation is still true in many parts of the cockpit today.

1.8 Operating Procedures

1.8.1 Use of SOPs & Checklists

This section deals with Standard Operating Procedures (SOPs) and one particular form of SOPs, checklists. The careful following of checklists is essential to safe aviation. The two examples of aviation incidents described in appendices B.2 and B.3 could both have been avoided had the prescribed checklists been properly read. In one of those incidents, an item was missed from one checklist (a *productive act*) and the pre-landing checklist (a *defence*) was not read at all. In the other incident, reading the "engine out" checklist would probably have saved the aircraft.

It must not, however, be thought that unconditional reading of checklists is the correct thing to do. As Sidney Dekker points out in his paper *"Failure to adapt or adaptations that fail: contrasting models on procedures and safety"*, the crash of Swissair Flight 111 off Nova Scotia in September 1998 could possibly have been avoided had the captain not overruled the first officer who wanted to descend rapidly, dump fuel early and land, possibly overweight, at Halifax. The captain insisted that the applicable checklists be read and thereby delayed the decision on dumping fuel. The aircraft became uncontrollable and crashed into the sea. As Dekker says:

> If rote rule following persists in the face of cues that suggest procedures should be adapted, this may lead to unsafe outcomes. People can be blamed for their inflexibility...
>
> If adaptations to unanticipated conditions are attempted without complete knowledge of circumstance or certainty of outcome, unsafe results may occur too. In this case people get blamed for their deviations...

[16] Available at `http://asrs.arc.nasa.gov/callback_issues/PDF_Files/cb_307.pdf`

1.8.2 Standard Operating Procedures

Standard Operating Procedures (SOPs) are issued by an operating company (airline, flight school, air taxi operation, etc.) and consist of written procedures to be followed in particular circumstances. The contents of an SOP are defined in section 723.107 of the CARs. They can be considered as lying in the *Line Management* layer of Reason's model.

One advantage of SOPs is that they provide consistency across an organisation—all members of a flight crew or maintenance organisation can be trained to expect the same activities at the same points in their work. This makes teams more effective, particularly when staff are moved between them.

For example, a particular airline might have an SOP for pre-flight weather checks of this form:

> Prior to each flight, the PIC (Pilot-in-Command) will obtain aviation weather reports and forecasts and analyse the following data to determine the effect on the proposed operations:
>
> - Latest NOTAM for the point of departure, route of flight, the destination and the alternate destination.
> - Surface weather observations for pertinent stations.
> - Forecasts for all pertinent routes and stations.
> - Reports or forecasts of severe weather, turbulence or icing which could affect the proposed flight.
> - Any known air traffic delays.
>
> Pilots will check weather forecasts sufficiently in advance of a proposed flight and notify Dispatch of any conditions that may affect passenger schedules. This includes checking weather forecasts the night before an early morning scheduled departure. The PIC may delegate some of these duties; however, he or she maintains the responsibility.

This portion of an SOP highlights several aspects of a good SOP:

- It specifies reasonably precisely what *must* be done while leaving some aspects to the discretion of the PIC (e.g., what could be included in "...all pertinent stations"?).
- It is written for the level of the person reading it. There is, for example, no unnecessary information about *how* the weather information should be

gathered—it is assumed that any PIC would know this.

- It specifies who has responsibility for ensuring that the process is followed, the PIC in this case.

Many aircraft incidents have been caused by pilots not following SOPs—see for example the transcripts given in appendix B. Given that most pilots would admit that the procedures in SOPs are sensible, the question arises of why they are sometimes ignored. As human beings, we do those actions which reward us with results that are reliable, positive and immediate. If an action does not give a tangible or quick result, there is little reinforcement for it. For example, a mechanic not following an SOP might give himself or herself more time for a coffee break. The negative consequences of deviating from the SOP might not be so immediately apparent.

In the case of the examples in appendix B, the immediate causes of not following the SOPs seem to have been complacency and fear. It is exactly to overcome these two threats to safety that the SOPs were written: to ensure that even a complacent pilot follows the process and to provide a framework to focus activities when the pilot is afraid. Unfortunately, in neither case did the pilots concerned take the time to follow the SOP.

Exercise 8 *Consider the following incident and describe some of the "holes" in the various layers of Reason's model that may have led to it:*

> *Pinnacle Airlines Flight 3701, a Bombardier RJ, crashed into a residential area south of Jefferson City Airport in the USA on 14th October 2004 while being vectored to the airport after a double engine flameout. During the flight, both engines flamed out after a pilot-induced aerodynamic stall and the pilots were unable to restart them. The captain and the first officer were killed, and the aircraft was destroyed. VMC prevailed at the time of the accident.*

The results of the investigation included the following:

- *The pilots' aggressive pitch-up ... during the ascent and their decision to operate the airplane at its maximum operating altitude (41,000 ft) were made for personal and not operational reasons.*
- *The improper airspeed during the climb demonstrated that the pilots did not understand how airspeed affects airplane performance and did not realise the importance of conducting the climb according to the published climb capability charts.*
- *The captain did not take the necessary steps to ensure that the first officer achieved the 300 knots or greater airspeed required for the windmill engine restart procedure and then did not demonstrate command authority by taking control of the airplane and accelerating it to at least 300 knots.*
- *Both engines experienced core lock because of the flameout from high power and high altitude, which resulted from the pilot-induced extreme conditions to which the engines were exposed, and the pilots' failure to achieve and maintain the target airspeed of 240 knots, which caused the engine cores to stop rotating.*

Anecdote 9 *SOPs are applicable not only to commercial enterprises: individual pilots may wish to devise their own. My personal SOP, for example, contains a number of rules and guidelines. An example of a rule is that, when flying IFR in the USA where it is not always necessary to file an alternate airport, I will always identify an alternate airport meeting the Canadian requirements. An example of a guideline is that I should never plan a flight where I have a compelling reason for being at the destination within three hours of the estimated time of arrival (i.e., avoid time pressure).*

1.8.3 Checklists & Manuals

Many pilots distinguish between "checklists" and "do-lists". "Do-lists" are lists of things to do, "checklists" are lists of things to check and both are forms of Standard Operating Procedures.

Most pre-takeoff checklists really *are* checklists because they are checking that everything has been done before takeoff. Many engine start "checklists" are, in contrast, "do-lists". This section calls both of these types of list a checklist but the distinction is useful and should be considered when developing lists—separate the things to be checked from the things to be done. A "do-list" is often not written down: it is performed as a cockpit flow: the pilot's hand moving perhaps from left-to-right across the cockpit setting items for an instrument descent. A checklist can then be applied to ensure that everything was done. One advantage of this is that, if the actions have to be repeated in a hurry then they will probably be done correctly, even if there is no time to run the checklist.

One problem with reading checklists is missing items on it. The chances of missing an item can be reduced by various techniques including:

- Numbering the items and reading out the numbers with the item. It is hard to ignore a gap in a numbered sequence, particularly if the number is read aloud: "..., six: check A, seven: check B, nine: check C". That is hard to read without immediately noticing that eight was missing.
- Writing the checklists in challenge-response form and using a passenger or other crew member to challenge you. An after-landing checklist might contain:

  1. **runway** *cleared*
  2. **throttle** *set to 1000 rpm*
  3. **flaps** *retracted*
  4. **carb heat** *cold*
  5. **landing light** *off*
  6. **transponder** *off*
  7. **ELT** *checked*
  8. **landing time** *recorded*

  The passenger reads the text in bold (including the number) and then waits for the pilot to complete the action and respond with the text in italics. This ensures that the pilot is not able to carry out the checklist without concentrating, and it involves the passenger in the execution of the flight—something that helps cockpit resource management.

What action should be taken when it is realised that, even with the precautions above, an item was missed earlier on the checklist? This must be a personal decision of the pilot: some pilots start the entire checklist again, others look at the items immediately before and immediately after the missed item. If these two items were performed, then only the missed item is performed.

1.8.4 The Case Against Checklists

Having stressed the importance of checklists, John Deakin's 1998 article *Throw Away That Stupid Checklist!*,[17] updated in 2020, is an interesting counterbalance. Instead of a written checklist for light aircraft, Deakin advocates an orderly (and repeatable!) "flow pattern" and the use of mnemonics (e.g., CIGFTPR[18] and GUMP[19]) for review checks. This is certainly the way many are taught to fly gliders ("CB-SIFT-CB"[20] being the review carried out before allowing the tow rope to be attached) and the way many pilots perform downwind checks, believing this to be an inappropriate time to be reading a checklist. In an article entitled *Habits, Not Checklists* in the July 2007 edition of *IFR* magazine, Frank Bowlin makes much the same point: do-lists should be replaced by mnemonics and habits; checklists should only be used to check that the items have been done. So, a checklist would not contain "Set Carb Heat Cold", instead it would contain "Check that the Carb Heat is Cold".

In considering Deakin's and Bowlin's articles, bear in mind section 602.60 of the CARs:

> *No person shall conduct a take-off in a power-driven aircraft, other than an ultra-light aeroplane, unless the following operational and emergency equipment is carried on board:*
>
> - *a checklist or placards that enable the aircraft to be operated in accordance with the limitations specified in the aircraft flight manual, aircraft operating manual, pilot operating handbook or any equivalent document provided by the manufacturer*

1.9 Interpersonal Relations

1.9.1 Communications

In his book *Fate is the Hunter*,[21] describing the relationships between members of flight crews in the 1930s and 1940s, Ernest Gann describes a Captain who is present to fly the aircraft and a First Officer present only to keep the cabin heater working and the passengers happy. The idea of teamwork seemed to have occurred to few Captains in those days. Today things are better but in his 1993 article *Teams, leaders and organizations: New directions for crew-oriented flight training*,[22] J Richard Hackman, reports the following experiences flying in the jump seats of various commercial airliners:

> Anyone who has logged much time watching cockpit crews has experienced both uplifting and depressing feelings. The first officer, who is flying the leg, calls for retraction of the flaps even as the captain's hand is moving toward the lever. The co-ordination is smooth and seamless. Or the captain, reflecting privately on the deteriorating weather at the destination muses "Probably we ought to take a look at the approach plates for the alternate," and the first officer, without a moment

[17] Available from AvWeb.
[18] Controls, Instruments, Gas, Flaps, Trim, Power, Radio
[19] Gas, Undercarriage, Mixture, Propeller
[20] Controls, Balance, Security, Instruments, Flaps, Trim, Canopy, Air Brakes.
[21] ISBN 978-0340007327
[22] Appears in *Cockpit Resource Management*, ISBN 978-0127500263.

> of hesitation responds "Yes I've got them right here ..." Watching a great crew operate can be as impressive as watching a superb dance company perform a well-rehearsed ballet.
>
> Watching other crews can make you wish you were somewhere else. The captain's hand moves towards the lever and then stops halfway, waiting, while the first officer pointedly keeps his eyes outside and his mouth shut. After some seconds of awkward silence, the first officer announces, "When I'm ready for flaps I'll call for them." And things go downhill from there. Or when a last-minute runway change results in both pilots, heads down, flipping pages hurriedly to find the new plate while the observer, his eyes alternating between the gauges and the traffic outside, hopes that one of them finds it soon.

The importance of crew resource management (CRM) is now universally accepted and CRM training is now a requirement for commercial pilots working under most regulatory bodies worldwide, including the FAA (USA) and EASA (Europe).

CRM addresses the cognitive and interpersonal skills needed to manage the flight in an organised manner. Cognitive skills are the mental processes used for gaining and maintaining situational awareness, for solving problems and for taking decisions. Interpersonal skills include communications and a range of behavioural activities associated with teamwork.

CRM is designed to foster a culture where the freedom to question authority is encouraged. This is a delicate subject for many organisations and certainly something that would not have been countenanced by some of Gann's Captains. So that supervisors understand that the questioning of authority need not be threatening and subordinates understand the correct way to question orders, training is required for both.

Todd Bishop of the *Error Prevention Institute* has published a five-step process that subordinates are encouraged to follow to maximise the chance of a successful outcome:

1. Get the Captain's attention by addressing him or her directly—"Hey Chief" or "Captain Smith".
2. State your concern in a direct manner—"We are 200 feet above our cleared altitude and still climbing".
3. State the problem as you see it—"In a moment we will bust our altitude".
4. State a solution—"Let's level off here manually and then reset altitude hold".
5. Obtain agreement (or buy-in)—"Does that sound good to you, Captain?"

These are difficult skills to master, as they require a change in interpersonal dynamics and organisational culture in many organisations. The cockpit transcript for the Air Florida accident at Washington National Airport, USA in 1982 when a Boeing 737 crashed shortly after takeoff because of airframe and engine icing contains the following exchange that contradicts almost every one of these five principles:

First Officer: It's a losing battle trying to de-ice these things. It gives you a false feeling of security, that's all it does."

Captain: Well, it satisfies the Feds.[23]

...

First Officer: Slushy runway, do you want me to do anything special for this or just go for it?

Captain: Unless you've got something special you'd like to do.

...

First Officer: God, look at that thing. That don't seem right, does it? Uh, that's not right.

Captain: Yes it is, there's eighty.

First Officer: Naw, I don't think that's right. Ah, maybe it is.

Captain: Hundred and twenty.

First Officer: I don't know

In all these communications the First Officer failed to convey the problem to the Captain: his sentences were incomplete, at no point did he define the problem and at no point did he suggest a solution. The transcript of a separate incident included in appendix B.2 on page 342 also shows a First Officer failing to make a clear statement of the problem to the Captain and failing to make a decision even though he was Pilot Flying.

CRM is not confined to multi-crew aircraft and, in general aviation aircraft, passengers often form part of the "crew" for CRM purposes. However, they can only become useful members of the crew when properly briefed. If an emergency occurs then the pilot is likely to be too busy to give detailed briefings—it is essential that these briefings be given on the ground before departure. SecureAv provides useful sample passenger briefing packs for passengers in both land and seaplanes on its website at `http://www.secureav.com/`. More information about passenger briefings can be found in chapter 11.

[23] Government Regulators

To encourage CRM thinking amongst general aviation pilots, Jefferson Koonce in his book *Human Factors in the Training of Pilots* recommends that, even in pre-solo training, two students be taken up at a time for a lesson. The Student Not Flying (SNF) helps scan for traffic and cautions the Student Flying (SF) when altitude or heading excursions occur or airspeed drops dangerously low. This way the SNF learns by observation and the SF learns to accept input from a person other than the instructor.

1.9.2 Operating Pressures

Numerous incidents have been recorded of pilots succumbing to pressures from non-pilots and making trips against their better judgement. It is often easy for a non-pilot to appeal successfully to the macho attitude of many pilots—see section 1.6.4: *"We know you can do it. We have every confidence in you."* At this point refusing to make the flight is seen as letting down the very people whose confidence one needs.

Other peer pressures that have to be resisted include "other people are flying in these conditions" and a statement from a "hangar flyer" that "in my day we flew in much worse conditions than these". That other people are flying should be seen as an opportunity to get PIREPs of the actual conditions, not as a challenge to be met. And boasts by hangar flyers without recent experience should be ignored.

As well as being subject to negative peer pressure, pilots can also inflict peer pressure on others, particularly young and impressionable new pilots. Telling such a pilot about an accident or violation or near accident that you have experienced is good pilot-to-pilot communication. But boasting about an accident, violation or near accident is extremely bad pilot-to-pilot communication. Owning up to our mistakes is helpful; glorifying them applies peer pressure to less experienced pilots.

Peer pressures can also have positive effects; for example, many people have stopped smoking because of peer pressure. With the publication of cockpit transcripts of non-sterile cockpits during takeoff and landing (see, for example, the transcript of the takeoff crash at Lexington, Kentucky, USA on 27th August 2006) it is hoped by some observers that peer pressure will lead to much more professional cockpits during these critical phases of flight.

1.10 Answers to Exercises

Some answers to the exercises in this chapter are included here. These answers are not meant to be definitive.

Exercise 1

The first reaction of most pilots reading a report such as this is: "pilot error: flying too low. I'd never be that stupid." Having this "first story", it is tempting to move on to the next report. However, benefit comes from imagining some of conditions that might be present in the deeper, "second stories":

- The two pilots were both new ultralight pilots and each had been handling the controls while experimenting with illusions caused by drift in such a slow aircraft. To do this they had come very close to the ground but were very aware of the fence at the end of the field. However, following the last exercise it was unclear who was actually flying the aircraft, and each pilot had thought the other was going to lift it over the fence. Unfortunately, neither did.
- The owner of the ultralight was demonstrating its manoeuvrability to his friend, also a pilot. At the end of one turn the aircraft rolled out facing directly into the setting sun and the pilot did not see the fence directly ahead.
- The owner of the ultralight had been demonstrating the takeoff performance of the aircraft and had unfortunately taken off below stall speed in ground effect. Seeing the fence ahead he pulled the nose up to clear it only for the increased drag to force the aircraft back down, causing an impact with the fence.

Perhaps none of these is the true story, but each is plausible and few pilots would be able to say that none of these situations could ever happen to them.

Exercise 2

The **productive act** here was Jill's error in not leaning the mixture: a "lapse" in the terms used in figure 1.3. Another productive act could have been not including the fuel gauges in her scan (possibly a "slip"). Without interviewing Jill, it is difficult to know the actual holes that aligned for this incident to occur, but the following are possibilities:

- The aviation regulations only call for pre-flight planning to include 30 minutes of fuel to be remaining in the tanks at the end of a day VFR flight. Perhaps this level is inadequate and represents a "hole" in the *Decision-Maker* layer.
- Jill's training might not have sufficiently stressed the importance of leaning the mixture. For example, if the mixture had been

consistently leaned on training flights, it would have been second nature to her. If not, this would represent a failure in training—a hole in the *Line Management* or even in the *Decision-Maker* layer.

- Generally aircraft manufacturers do not include non-leaned fuel burn figures in their handbooks. Unless pilots fly aircraft fitted with fuel burn gauges, they don't have a feel for the difference in fuel burn with correct leaning. Perhaps regulations ought to be in place from the *Decision-Makers* requiring manufacturers to publish the un-leaned fuel burn.
- This could have been Jill's first extended cross-country. In this case, she may have been feeling particularly nervous or over-excited—a *Precondition* for making an error.
- The *defence* against this incident was, of course, the fuel gauges. However, these are often very inaccurate in light aircraft.

Exercise 3

Viewed in retrospect, there are many factors associated with the decision to be made here: the illegality of entering cloud on a VFR flight-plan, the danger of entering cloud (a summary of the 1993 FAA study, *178 seconds to live,* is included as Appendix E on page 351), and the danger of starting the descent if the controller can see traffic below you.

In the actual situation, you do not have time to weigh all of these and make a decision. Nor, in reality, do you have time to apply the DECIDE model but, for completeness, here are its steps:

Detect Change. There is a clear change here from an expected interchange with a controller. One would expect to hear "Canadian Papa Tango November, descend at your discretion, remain VFR at all times."

Estimate its Significance. This change in normal conditions is serious: descent could mean a collision with another aircraft or terrain, continuing flying without descending will mean entering cloud and recreating the circumstances outlined in Appendix E.

Choose a Safe Outcome. The required safe outcome here is that the aircraft, pilot and passengers remain safe.

Identify Possible Actions. You are invited to create a list of possible actions. These might include:

- descending and telling the controller to redirect the other traffic (arguing to yourself, if necessary, that a controller cannot give an instruction that would cause you to break an aviation regulation).
- maintaining the current heading and altitude and accepting that you will enter cloud.
- turning onto a different heading while maintaining altitude and informing the controller of your action—possibly asking for a suitable heading.

Do Best Option. As with any decision-making, it is not clear which is the best option. It also depends on your attitude: if you are anti-authoritarian then you may relish breaking an aviation regulation. If you are an IFR-rated pilot in an IFR-equipped aircraft, a few minutes in cloud is likely to be inconsequential and it might be best to maintain heading and altitude. If you are a VFR pilot with a little "hood" time some years previously, this would probably be the worst option.

Evaluate the Effect. Whatever action you take, continue to monitor the safety of the aircraft and re-assess as necessary.

The last two steps in this DECIDE model are discussed further in exercise 6 on page 20.

Exercise 4

1. *Initiate Process.* Fred believes that a risk exists and is asked to define the issue precisely. As every member of the group will be affected, it is agreed that every member of the group is a stakeholder in the decision.
2. *Perform Preliminary Analysis.* In this phase Fred and other group members might be asked to gather information:
   - Are there any statistics that indicate that the chance of an accident increases after a particular period of absence from flying?
   - Is the risk affected by the total hours the pilot has?
   - What do other groups have in their rules?

   Then the decision would be made as to whether the potential risk is such that flying should stop until a conclusion is reached.
3. *Estimate Risk.* The group gets together and reviews the information gathered in the previous step. Is there a genuine risk if currency requirements are not added to the agreement? If not, the process can be stopped at this point. If so, then the next step is taken.

4. *Evaluate the Risk Activity.* A more complete analysis of the consequences of the proposed action is carried out—would a currency rule make membership of the group less attractive (and therefore worth less when a share is sold)? If so, is the financial loss outweighed by the mitigation of risk?
5. *Control Risk.* During this step possible actions are tabled and compared. Should a currency rule only apply to new group members? Should the rule only apply to pilots with fewer than 500 hours? Should a 1 month or 3 month currency be required? How should currency be regained once lost? A decision is made and all members of the group are given the opportunity to comment.
6. *Take Action.* The new rule, agreed by the group members, is added to the bylaws.
7. *Monitor Impact.* Once the new rule is in place it is monitored for its economic and social impacts—has the amount of flying dropped substantially, making the aircraft less economical for the group? Has the cost of landing mishaps reduced because pilots are more current? Has the new rule introduced new risks (e.g., members flying for very short periods just inside the currency period, rather than flying with an instructor to regain currency once it has lapsed)?

Exercise 5

This example is taken from document AC 60-22. Action 1 is clearly the action of a pilot who feels **invulnerable**—"nothing can happen to me!" Action 2, particularly in wanting to impress people on the ground, indicates a **macho** attitude. Thinking that checklists are stupid, action 3, indicates that the pilot thinks that aircraft designers, the government and instructors are wrong—an **anti-authoritarian** attitude. Action 4 is the action of an **impulsive** person doing something (anything!) quickly; depending on the aircraft and wind speed and direction, a better decision might be to land without flaps or to go around. The pilot in action 5 seems to have handed control of the aircraft to the wind—an act of utter **resignation.**

Exercise 6

1. **Anti-Authority** (don't tell me!). The controller having told this type of pilot what to do (fly into the cloud), the reaction is possibly to refuse the instruction and start the descent. In this case this might, of course, be the correct action, but reached for the wrong reasons.
2. **Impulsive** (do something quickly!). This type of person is likely to do something immediately: probably start the descent as the cloud is looming because surely some action has to be taken.
3. **Invulnerable** (it won't happen to me). Since this pilot believes that accidents happen to others, he or she could decide to take any of the possible actions.
4. **Macho** (I can do it). These pilots are probably determined to demonstrate to the controller (or, more probably, passengers) that they can fly in cloud. The controller has given them the perfect excuse to demonstrate their skills.
5. **Resigned** (what's the use?). These pilots are unlikely to consider any action, since whether they fly into the cloud or descend in the path of the other aircraft is really outside their control. Since an external agency, the controller, has told them what to do (fly into the cloud) they are likely to follow the instruction without regard to the danger.

Exercise 7

At least impulsivity and invulnerability and possibly a macho attitude (showing off to my wife and son). Given the number of times one hears about the dangers of flying close to thunderstorms in flight training, there was also an element of anti-authority—"I know best." All-in-all, this was a really bad decision.

Exercise 8

There are numerous possible holes in the various layers of Reason's model but two are perhaps particularly important:

1. The pilots did not have sufficient grasp of the aerodynamic principles of what would happen to the jet engines at very high altitude and low speed. This is a training issue in the **line management** layer of Reason's model. From the complete report on the incident, it appears that this type of aerodynamic training was considered unnecessary because the aircraft, if flown according to the SOPs, would never experience this condition. All stall training had been carried out at low altitudes. As one commentator, Richard N. Aarons, has written:

   > Recently, the industry has witnessed a number of accidents involving commercial

> and air transport rated pilots who seem to lack fundamental knowledge of aerodynamics, meteorology, powerplant theory and basic airmanship. (This problem seems more prevalent in the airlines than it is in corporate aviation, perhaps because the airlines tend to pay low initial salaries and hire from the bottom of the experience pool.)

The first officer in this incident had 565 hours total pilot time, with about 140 hours as PIC.

2. Having had both engines fail, the two pilots did not follow the SOPs for such an event. These required the aircraft be put into a dive to achieve a speed of at least 300 knots to restart the engines. This represents a **productive activity** in Reason's terms. The defence mechanism should have been the copilot taking the initiative to read the appropriate checklist but, in the circumstances of a high-altitude flame out at night, a relatively inexperienced copilot might well have leaned too much on the captain for leadership.

Chapter 2

Human Factors: Physiology

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2.1 Introduction

Note that various books are referenced in this chapter by title only: for full details, including ISBNs, see section 1.2 on page 8.

2.2 Physiological Aspects of the Operating Environment

This section describes some of the physiological aspects of a pilot's normal working environment that can potentially become *preconditions* in Reason's model—setting the scene for accidents to occur: see section 1.4.2 on page 10.

2.2.1 Hypoxia

A human body needs oxygen to operate. Air is brought into the lungs when a person breaths in, and the oxygen in it is transferred to the blood in the lungs. The blood then carries the oxygen to other parts of the body. Hypoxia occurs when insufficient oxygen is available to the body. This can occur in the following situations:

- If there is insufficient oxygen in the air being inhaled. This is known as *Hypoxic Hypoxia*.

  Drowning is an extreme form of Hypoxic Hypoxia: the lungs do not have enough free oxygen to be transported around the body. A less extreme example occurs when flying an unpressurised aircraft at high altitude.

- If the blood is not carrying its normal amount of oxygen from the lungs to the other parts of the body. This is known as *Anæmic Hypoxia*.

  This may be caused by a lack of blood cells to carry the oxygen (for example, after donating blood) or by the blood's inability to carry oxygen because it is already carrying carbon monoxide (for example, from a leaking exhaust system, or cigarettes).

- If the blood is carrying its normal amount of oxygen but the circulation of the blood is impeded. This is known as *Stagnant Hypoxia*.

  This can be caused by medical conditions that constrict the blood vessels (e.g., Raynaud's or Buerger's disease). It can also be caused by blood draining to the feet during acrobatic flight or by exposure to cold.

- If the blood is carrying the oxygen to the parts of the body but those parts are not accepting it in sufficient volumes. This is known as *Histoxic Hypoxia*.

  This is often caused by alcohol or other drugs in the body.

	Symptoms observed by ...	
	... an External Observer	... the Hypoxic Person
Mental Condition	Euphoria Inability to perform simple tasks Confusion Impaired Judgement Aggression	Euphoria Excellent Performance Clarity of thought Normal judgement
Physical Condition	Increased respiration Poor Co-ordination Blue colour of skin Night vision significantly reduced	Dizziness Nausea Headache Tingling Blurring or tunnel vision

Figure 2.1: Symptoms of Hypoxia

The symptoms of hypoxia are often not noticed by the sufferer: see figure 2.1. The important point to be noted from the figure is that the person suffering from hypoxia is often unaware of the condition and, indeed, believes that he or she is performing better than normal.

The effects of the different types of hypoxia are cumulative: a pilot who smokes (anæmic hypoxia), has been recently drinking alcohol (histoxic hypoxia) and is flying at altitude without supplemental oxygen (hypoxic hypoxia) will suffer the cumulative effect of these.

The most common form of hypoxia for pilots is hypoxic hypoxia caused by flying in unpressurised aircraft at altitudes where the air contains an insufficient partial pressure of oxygen.[1] The component of the blood that carries oxygen around the body is known as hæmoglobin, and Figure 2.2 illustrates the reduction in the saturation of oxygen in the hæmoglobin at different altitudes for an "average" person. The higher an aircraft flies, the lower the atmospheric pressure. At sea level, atmospheric pressure is 760 mm Hg ($\approx 29.92''$ Hg),[2] of which oxygen contributes a partial pressure of 150 mm Hg. At a pressure altitude of 10,000 ft the total atmospheric pressure has dropped to 523 mm Hg ($20.59''$ Hg), of which oxygen contributes a partial pressure of only 60 mm Hg.

The drop in oxygen pressure causes the saturation of the blood to reduce as illustrated in figure 2.2: in a "normal" person, by 10,000 ft the saturation has dropped to 90% and is rolling off rapidly as altitude increases. The saturation level in a normal person at rest at sea-level is greater than 98% and any value below 90% when resting is officially termed hypoxia. At this level, the symptoms listed in figure 2.1 may begin.

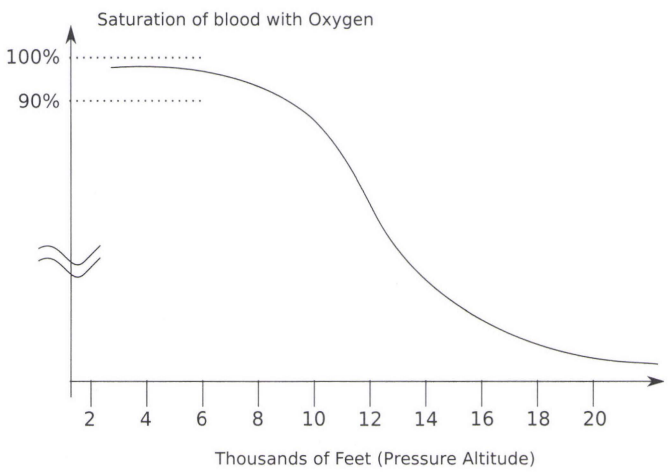

Figure 2.2: Oxyhæmoglobin Disassociation Curve

Figure 2.3: A Fingertip Pulse Oximeter

[1] In a mixture of gases such as air, each gas has a partial pressure, which is the pressure the gas would have if it alone occupied the volume.

[2] Hg is the chemical symbol for mercury. The meaning of measuring pressure in height of mercury is explained in section 3.9 on page 51.

The actual curve of saturation level against altitude (figure 2.2) varies greatly from person to person and you are encouraged to use an *oximeter* to measure the actual saturation of *your* blood at different altitudes. These devices are available from pilot supply shops and typically fit over the tip of a finger, shining infrared and visible light through the flesh and measuring the level of oxygen absorption from the blood cells—see figure 2.3. With an oximeter, the altitude (strictly *pressure altitude*) at which the saturation of your blood drops below 91% should be noted: this is the start of the rapid decline in the curve in figure 2.2, and remaining at this level of saturation avoids putting unnecessary load on the heart. If you are young and very fit, this may occur at 11,000 ft ASL. If you are elderly or unfit, it may occur as low as 5,000 ft ASL. For most adults with no underlying medical conditions, the 91% level occurs between 8,000 and 10,000 ft ASL. This is the altitude above which you should use supplemental oxygen during daylight flights.

The only way to avoid hypoxic hypoxia is to maintain a high level of saturation of oxygen in the blood by using supplemental oxygen when flying above your own personal 91% saturation level during the day or half that altitude at night (because of the effects on night vision). Because of the low atmospheric pressure at altitude, even using supplemental oxygen is no guarantee of avoiding hypoxia—a situation described in Jon Krakauer's *Into Thin Air*.[3]

Hypoxia is particularly acute for smokers, obese people and the elderly. For smokers, the carbon monoxide in tobacco smoke combines 210 times more readily with the blood's hæmoglobin than oxygen does. This causes Anæmic Hypoxia at altitudes about 5,000 ft lower than for non-smokers. Smokers are therefore advised to use oxygen above 5,000 ft ASL by day and at all altitudes at night.

At extreme altitudes, hypoxia can cause unconsciousness or death. Figure 2.4 gives some approximate figures for the time of useful consciousness at various pressure altitudes.

Altitude	Sitting Quietly	Moderate Activity
20,000 ft	12 mins	5 mins
25,000 ft	3 mins	2 mins
30,000 ft	75 secs	45 secs
35,000 ft	45 secs	30 secs
40,000 ft	30 secs	18 secs

Figure 2.4: Times of Useful Consciousness

[3]ISBN 978-0-330-35397-7

Hypoxia, in Reason's terms, constitutes a *precondition* for the pilot to make an error. Many aviation accidents have occurred because the pilot was unknowingly suffering from hypoxia—not only was the pilot unable to make good decisions, he or she believed that the decisions being made were good. Robert Cohn's book *They Called It Pilot Error*[4] describes a number of aviation incidents attributed to poor decision-making under the influence of hypoxia. These include several cases of normally cautious pilots without supplemental oxygen who, although low on fuel, flew over a number of airports and eventually ran out of fuel short of their destination.

2.2.2 Hyperventilation

A healthy person takes about 12 to 15 breaths each minute. Hyperventilation is simply breathing too fast and too deeply. This can be caused by stress or anxiety, particularly when you are concentrating on a difficult task: for example, a non-precision approach to minimum descent altitude or nursing a rough-running engine over mountainous terrain at night. Panic can exacerbate hyperventilation.

There is another condition, known as tachypnea (from the Greek for "rapid breathing") that should not be confused with hyperventilation. This occurs when the breathing rate increases after heavy exercise to ensure sufficient gas-exchange to the body and is the normal reaction to the body needing more oxygen.

Physiologically, hyperventilation leads to too little carbon dioxide in the lungs and blood relative to the amount of oxygen. The blood becomes more alkaline (the pH value rises) and this changes the acid-base balance in the body, causing brain hypoxia. The symptoms are progressive, beginning with dizziness and "pins and needles" in the hands or feet and then muscular spasms and eventually unconsciousness.

The treatment for hyperventilation is to slow the breathing rate to one breath every five seconds (12 breathes per minute). It can also be helpful to hold a conversation or to breathe in and out of a paper bag (the aircraft's sick bag perhaps) since this increases the concentration of carbon dioxide in the inhaled air. The book *Human Factors in the Training of Pilots*[5] by Jefferson M Koonce even recommends singing to yourself if there is no passenger with whom you can hold a conversation. (It is interesting to speculate about the song one would sing with a rough-running engine over mountainous terrain at night![6])

[4]ISBN 978-0-830-64463-6

[5]ISBN 978-0-415-25361-1

[6]I notice that when my wife was proof-reading this book, she added a comment to this statement proposing Dido's lament from Purcell's Dido and Aeneas: "Remember me, but ah, forget my fate!"

2.2.3 Gas Expansion

At 18,000 ft, the atmospheric pressure is half of that at sea-level. As pressure reduces, the volume of a gas increases (Boyle's Law). Many general aviation pilots are surprised when the large bag of potato chips explodes in the luggage compartment of their unpressurised aircraft as they climb to higher altitudes. Most bags cannot tolerate the gases within them doubling in volume without exploding.

Unfortunately, there can also be trapped gases within the human body and these also attempt to expand, often resulting in acute pain. These pockets of air in the body include the following:

- **The middle ear.** The eardrum is a membrane about as thick as a piece of normal writing paper that seals the middle ear cavity where the hearing organs are situated—see figure 2.5. The only passage for gases in the middle ear to escape is through a thin tube called the *Eustachian Tube* that links the inner ear to the back of the throat (the nasopharynx). When the external pressure changes, air must flow through the eustachian tube to keep the gases in the middle ear at the same pressure.

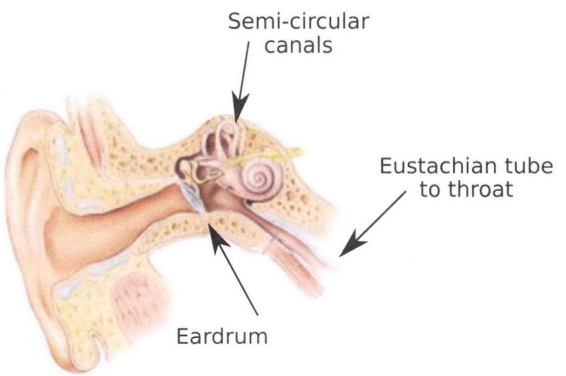

Figure 2.5: The Inner Ear (NASA)

  Where the eustachian tube enters the throat there is a soft lip-like opening and, as a pilot ascends, air flows from the inner ear along the eustachian tube to the throat. During a descent, however, as air tries to pass from the throat to the middle ear, the soft lip acts as a valve and is more difficult to open, particularly if the pilot has a cold, allergic symptoms or a throat infection. If air cannot pass through the eustachian tube to the inner ear, the pressure inside the ear becomes lower than that outside, causing the ear drum to be pushed inwards. This causes a condition known as *Barotitis* which results in difficulty in hearing, pain and, if severe enough, the rupture of the ear drum causing bleeding from the ear.

  The remedy is to try to open the soft lip at the end of the eustachian tube by opening the mouth widely, yawning, or swallowing with the nose closed. A technique known as the Valsalva Manœuvre can also be tried. This consists of holding the nose and blowing gently against closed lips until the ear "pops".

  The strong recommendation arising from the effects of a blocked eustachian tube is never to fly when you have a cold. The pain, particularly in descent, is a precondition in Reason's model for you to make an error.

- **The sinuses.** These are air-filled cavities located in the dense portions of the bones of the skull. They reduce the overall weight of the skull and exist in four left and right pairs. The frontal sinuses are positioned behind the forehead and the maxillary sinuses are behind the cheeks. Air gets into the sinuses through small openings in the bones that connect to the nasal passageways, called ostia.

  If these openings become blocked, the air pressure within the sinuses cannot equalise with the air pressure outside (and the mucus in the sinuses cannot drain out, providing an area for infection). This is known as *Aerosinusitis* or *Barosinusitis.* The blockage can be caused by anything that causes swelling of the tissue lining of the passageway including colds, allergies and tissue irritants (over-the-counter nasal sprays, cigarette smoke).

  As with the blockage of the eustachian tube, the low pressure inside a sinus as the aircraft descends into higher outside pressures can cause acute pain.

- **The teeth.** When a tooth has been filled, it is possible for a parcel of air to be trapped inside it. As the aircraft ascends and the external pressure drops, the air inside the tooth exerts pressure on the tooth and this can cause a severe toothache. This condition is known as *Barodontalgia* and can only be cured by another visit to the dentist.

  After dental work, you are advised to be careful when flying—perhaps ascending to 1,000 ft and waiting to see whether there is any effect, then climbing to 2,000 ft and waiting again, and so on. At the first sign of pain or discomfort, descend immediately.

- **The bowels.** For most pilots the expansion of air trapped in the bowel during ascent is more of an embarrassment than a real problem. However, for people with bowel disease or an obstructed loop of bowel, the expansion of gas during an ascent could cause rupture of the weakened areas of the bowel.

Special rules are issued by Health Canada to nurses and doctors accompanying patients evacuated by aircraft covering the identification and treatment of many of the problems that can be caused by gas expansion at altitude.

Another aspect of gas expansion is the speed at which it takes place. A fully-loaded Cessna 172 climbing from sea level to 10,000 ft may provide the body with sufficient time to compensate for the changing external air pressure, whereas a passenger jet suddenly depressurising at 35,000 ft does not. In the case of sudden depressurisation at high altitude, the cabin air will expand and cool, contributing fogging (that may be mistaken for smoke) to the effects of hypoxia and gas expansion. The only recourse to such decompression is to descend as quickly as possible.

2.2.4 Personal Health/Fitness

Being healthy and fit provides certain advantages to a pilot, including the following:

- Better muscle and aerobic conditioning allows a pilot better to tolerate fatigue, hypoxia and G-accelerations.
- Fitness improves self-confidence and this leads to a more positive attitude when flying.
- An active body has a better conditioned heart, resulting in better blood flow throughout the body.

2.2.5 Diet/Nutrition

Pilots perform better if they are eating a balanced diet.

One effect of a poor diet is hypoglycemia—low blood sugar. This occurs when the blood glucose (blood sugar) level drops too low to provide enough energy for the body's activities. This can happen when you eat food with a high refined-sugar content (e.g., doughnuts, soft drinks) and get a sugar "high" followed by a rapid drop in blood sugar.

Another effect of a poor diet is dehydration. This can be caused simply by flying for an extended period without a drink, but it is exacerbated by caffeine (see page 38), alcohol or some medications. Many studies have been made into the effect of dehydration on pilots. The following quotations are taken from *Dehydration Presents Unique Risks for Pilots* in the July-August 2001 edition of *Human Factors & Aviation Medicine*:

> When a person is dehydrated, the concentration of sodium in the blood usually rises. The person becomes thirsty and drinks. If water consumption is not adequate to offset water loss, the kidneys excrete less urine and perspiration decreases. Some of the water in the body's cells replaces water in the bloodstream, so the cells begin to dry out and to stop functioning properly. The malfunctioning of brain cells can lead to confusion, one of the primary symptoms of severe dehydration. Typically, dehydration results in the loss of electrolytes as well as the loss of water, and the depletion of electrolytes slows the movement of water from the cells into the blood. ... Mild instances of dehydration can be resolved by drinking water. If electrolytes—especially sodium and potassium—have been depleted, they must be replaced. Commercially available drinks have been formulated to replace electrolytes lost during exercise, but other non-caffeinated liquids are equally effective when they are consumed with salt.

As a pilot, you are advised to carry water or electrolytes in the aircraft and rehydrate the body before starting an approach, particularly on a hot day.

2.2.6 Medications & Substance Abuse

In Transport Canada's terminology "substance abuse" refers to abusing the human body by applying drugs to it. For aviation purposes, drugs can be divided into medications and those used for recreational purposes.

You must inform any doctor or optometrist that you consult that you are a pilot (see section 14.1 on page 307). However, many doctors and optometrists have no specialised knowledge about the medical needs of a pilot. For this reason it is essential that an aviation medical examiner checks any medicines you buy over-the-counter or are prescribed for you.

Medications can be divided into those that are designed to depress the activity of the central nervous system, those that are designed to simulate it, and others. Many depressants (e.g., antihistamines, codeine, valium, ibuprofen (Advil)) not only cause drowsiness but also vertigo—a reaction that can kill, particularly when in IMC. Many stimulants (e.g., some cold relief products) cause constriction of the blood vessels, and this causes mucous membranes such as the nasal passages and eyes to dry up—this is their intended response to give relief from a head cold. Unfortunately the dryness of the eyes (also caused by some depressants) reduces their ability to absorb oxygen, reducing the pilot's vision and making maps and approach plates difficult or impossible to read.

Some pilots believe that "natural" products must be effectively harmless. It should be remembered that morphine, aspirin and other powerful drugs are completely natural.

Recreational drugs include alcohol, caffeine, cannabis and cocaine. The only one of these explicitly addressed

by name by in the CARs is alcohol. Section 602.03 of the CARs says that:

> No person shall act as a crew member of an aircraft
>
> - within twelve hours after consuming an alcoholic beverage;
> - while under the influence of alcohol; or
> - while using any drug that impairs the person's faculties to the extent that the safety of the aircraft or of persons on board the aircraft is endangered in any way.

Most pilots remember the first of these, "12 hours bottle to throttle", but forget the second. An alcoholic drink taken 15 hours previously, but still influencing you, prevents you flying as a crew member.

Alcohol is a sedative and depressant that has serious impact on the higher brain centres, increasing reaction time, decreasing motor co-ordination and impairing judgement. Alcohol is also believed to move from the blood into the fluid (endolymph) in the inner ear, reducing its specific density. This reduced viscosity produces exaggerated vestibular stimulation during movement, something of obvious concern to a pilot in IMC. Tests indicate that the effect of alcohol on the inner ear can last for up to 34 hours after five or six drinks.

Alcohol is broken down in the body at a rate that is a function of the individual's metabolism. No matter what your grandmother taught you about drinking raw eggs beaten up in milk, or what you have heard about drinking strong coffee or breathing pure oxygen, you cannot cause your body to metabolise alcohol faster than its standard rate.

Caffeine is also an interesting drug. It is an antidepressant and stimulant for which it can take many months of abstinence to break dependency. It is also a strong diuretic that leads to dehydration through urination.

The other recreational drugs tend to have negative effects on perceptual ability, judgement and decision-making. Like alcohol they may also prevent the body's cells taking up oxygen from the blood—leading to hystoxic hypoxia—see section 2.2.1.

In November 2017, Transport Canada officials told delegates to the Air Transport Association of Canada meeting that any amount of TCH, the psychoactive chemical in cannabis, found in a pilot's bloodstream would result in immediate licence suspension until the body was clear of TCH. Unlike ethanol, TCH attaches to body fat and can persist for long periods of time after a single exposure.

2.2.7 Effects of Cold

The range of temperatures for which the skin on the human body is at "physiological zero", i.e., does not sense being hot or cold, is small: from about 29° to 32°C.[7] The thermal adaptors on the skin extend this comfort range spacing to approximately 18° to 40°C.

Outside these ranges, pilots will feel hot or cold. The effects of prolonged exposure to cold are shivering, inability to concentrate on tasks and lethargy.

When air flows over the skin, it causes evaporation and the sense that the temperature is actually colder than it really is. There are various formulæ used to calculate the equivalent temperature at various wind speeds, the so-called wind-chill temperature, but the most commonly used is that agreed in 2001 between the Meteorological Services of Canada and the National Weather Service of the USA. This is based on the formulæ devised in 1945 by two Antarctic explorers, Paul Siple and Charles Passel. It is not necessary for the Transport Canada examination to know the formula but, for completeness, it is as follows:

$$T_{wc} = 13.12 + 0.6215T_a - (11.37 - 0.3965T_a)\left(\frac{V}{0.53}\right)^{0.16} \quad (2.1)$$

where T_{wc} is the wind-chill temperature, V is the wind speed in knots and T_a is the actual temperature in degrees Celsius.

Exercise 9 *The wind is reported to be blowing at 19 knots and the outside air temperature is −20° C. What will the apparent temperature be while performing the pre-flight checks on the ramp?*

Possible answers to the exercises are given at the end of the chapter, starting on page 47.

Anecdote 10 *I was once travelling as a passenger in the right seat of a low-wing, light aircraft, travelling at approximately 115 knots, when the passenger door opened. The outside air temperature was approximately −20° C and, as the wind rushed through the cabin (taking the map out of the door), I did not have the presence of mind to work out the wind-chill temperature. Equation 2.1 is not intended for use at such high wind-speeds but it gives an approximate wind chill temperature of −57° C! It certainly felt like that; but rather than performing the calculation, I was*

[7] See, for example, *Body Senses* by Robert Kastenbaum in *The Encyclopedia of Adult Development*, 1993

speaking with the controllers at the closest airport, Ottawa International, to request an immediate landing.

Of course, we normally avoid exposure to cold by wearing suitable clothes, but it is important to remember that a large proportion of the body's heat is lost through the head—even those with a good hair cover should wear a warm hat in cold weather. When flying in a heated aircraft in cold weather, ensure that you are carrying sufficient warm clothing to survive outside the aircraft following a forced landing, or inside the aircraft should the heater fail. Otherwise hypothermia and frostbite can occur very quickly.

2.2.8 Effects of Heat

The effective temperature in hot weather is a function of the actual temperature and the amount of moisture in the air. The more moisture in the air, the less sweat will evaporate and the hotter a person will feel.

In most general aviation aircraft a high ambient temperature is not an issue in flight: moving air can normally be directed into the cabin to increase the evaporation of sweat. On the ground, while following a checklist, copying a clearance or taxiing, the "greenhouse" effect of the small cockpit with many closed windows can make the interior of an aircraft very uncomfortable. This type of environment can cause a decrease in both mental and physical performance. In his 1993 book *Human Factors in Flight*,[8] Frank Hawkins said that "heat has a more adverse effect on mental performance than cold". Every pilot should anticipate this reduction in mental performance and compensate for it.

2.2.9 Noise/Vibration

Most general aviation cockpits are noisy and subject to vibration. For some of the effects of noise on the pilot, see section 2.3.

Noise is just a particular form of vibration, the frequency of which lies within the range of hearing. Other vibrations, particularly turbulence around the aircraft's vertical axis (i.e., yaw), are also detrimental to the pilot—causing fatigue, loss of visual acuity and, in some cases, neck and back pain. There have been numerous studies into the effect of whole-body vibration (WBV) on performance and the general result seems to be that 20-25 Hz vibration is particularly detrimental to pilot performance. In modern general aviation aircraft the construction of the seats has been given a lot more thought with the aims of increasing comfort and decreasing the level of vibration transmitted to the crew and passengers.

[8] ISBN 978-1-857-42135-4

2.2.10 Toxic Hazards

The primary toxic hazard likely to be met in flight is carbon monoxide. As described on pages 33 and 35, carbon monoxide is a leading cause of Anæmic Hypoxia. The main sources of carbon monoxide are cigarettes and leaks in the aircraft's exhaust system—between 3% and 9% of the exhaust fumes from reciprocating engines are carbon monoxide. The exhaust gases, including the carbon monoxide, may be brought into the cockpit through the cabin heating system from leaks in the exhaust and, if you are smelling exhaust fumes in the cockpit, you are almost certainly also inhaling carbon monoxide.

The symptoms of mild carbon monoxide poisoning are headache, nausea, dizziness and fatigue—all preconditions for making an error. Severe exposure leads to unconsciousness, coma and death. If a passenger or crew member is suffering from any of the early symptoms of carbon monoxide poisoning, then cabin heat should be turned off, as much fresh air as possible should be brought into the cabin and the sufferer should be put onto supplemental oxygen. This will not bring immediate relief but it will prevent the problem from getting worse.

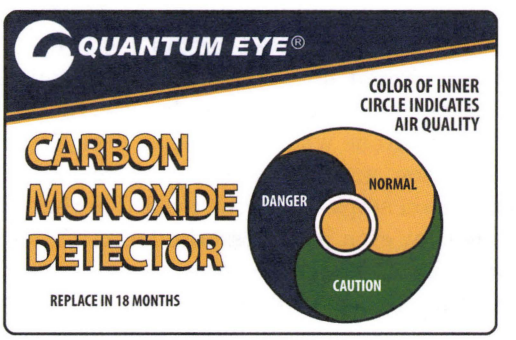

Figure 2.6: A Carbon Monoxide Detector (Quantum Group)

Carbon monoxide is odourless and colourless, so a human has no direct method of detecting it in the cockpit. Various detectors are available on the market, ranging from spot-type detectors (see figure 2.6), to battery-operated devices developed for residential use. The major problems with the spot-type detectors are:

- that they are relatively slow to respond, and most do not differentiate between a short exposure to a high concentration and a long exposure to a low concentration. Additionally, some spot-type detectors do not distinguish between carbon monoxide and other chemicals such as air fresheners. Use products with a so-called "Getter".

- that they have a finite life and, even though this is clearly marked on the sensor, many pilots do not replace them regularly.

In addition to carbon monoxide, the cockpit may also contain other toxic gases: ozone, the products of a fire and, for crop sprayers, the extremely toxic spray chemicals.

2.2.11 Decompression

When scuba divers ascend rapidly from a dive deeper than about 10 metres,[9] the nitrogen in the compressed air being breathed can be passed into the blood and transported around the body as small bubbles. The emergence of bubbles is similar to opening a bottle of bubbly wine: while the wine is corked and under pressure there are no bubbles; when the cork is removed and the pressure above the wine lowered, bubbles immediately appear.

The condition is referred to by divers as the *Bends* and, if the bubbles escape through the lungs, no problem occurs. If, however, the bubbles find their way into small blood vessels, they can block the circulation and result in anything from itchy sensations to severe joint pains and even death.

When flying, similar problems can occur when the external air pressure is halved—at about 18,000 ft.

Participating in any form of flying, whether in a pressurised or unpressurised aircraft (since even pressurised aircraft have a cabin pressure equivalent to about 8,000 ft ASL), can obviously exacerbate a problem for anyone who has recently been Scuba diving. For this reason, anyone who has been diving when decompression stops have been needed during ascent, should not fly, even in a pressurised aircraft, for at least 24 hours after the last dive. After deep diving, the period before flying should be even longer.

2.3 Hearing

The interior of most general aviation aircraft is a noisy environment. Not only does this induce stress and fatigue in a pilot, it can also damage hearing, often referred to as "noise-induced hearing loss". This results from permanent damage to the receptors in the inner ear that cannot be recovered by periods spent in quiet conditions.

The USA's National Institute for Occupational Safety (NIOSH) recommends that, given a noise level, L (in dBA), the maximum duration to which a person should be exposed to that noise (in minutes), is given by

$$t = \frac{480}{2^{\frac{L-85}{3}}} \tag{2.2}$$

The typical noise level in a light aircraft (for example, a Cessna 172) is 84 to 106 dBA. Taking 95 dBA as an approximation, equation 2.2 indicates that the longest unprotected exposure should be about 48 minutes. This illustrates the need to wear some form of ear protection in piston-engine aircraft. The almost ubiquitous use of headphones, particularly those with active noise reduction, and intercoms in general aviation aircraft today helps to mitigate hearing loss but some damage still occurs.

In contrast, the measured noise levels in commercial airliners range from 75 dBA (Airbus A320 family) down to below 60 dBA (Airbus A380): allowing effectively unlimited exposure without hearing damage.

Hearing also deteriorates with age, particularly the detection of high frequencies.

2.4 Positive & Negative "G"

Apart from the forces acting on an aircraft in a banked turn, with which this topic is related, "G Force" is perhaps the most misunderstood concept in aviation. Pilots often talk about "G Force" when they really mean "g acceleration". The symbol g is used to represent the acceleration that a dropped body experiences close to the surface of the earth,[10] about 9.8 metres per second per second (about 32 ft per second per second).

As described in section 3.8 on page 51, a person with a *mass* of 50 kg has a *weight* on the surface of the earth of $9.8 \times 50 = 490$ newtons. If the person moved to the moon where $g = 1.6$ metres per second per second, his or her mass would remain unchanged at 50 kg but the weight would be $1.6 \times 50 = 80$ newtons.

During various manoeuvres in the air, the acceleration of gravity downwards can be made to change. For example, if a 50 kg pilot is flying an aircraft in straight and level flight, the force acting upwards on her by the seat is 490 newtons, her normal weight. If she then puts the aircraft into a steep dive and pulls up abruptly, she (and the airframe) are accelerated upwards. If this acceleration happened to be 9.8 metres per second per second then she (and the airframe) would be experiencing a net acceleration of $9.8 + 9.8 = 19.6$ metres per second per second and her weight would be $19.6 \times 50 = 980$ newtons. She would feel twice as heavy, her jaw might sag and she would be said to be experiencing "positive Gs". Similarly, when pushing the nose downwards at the top of a climb, the pilot would

[9] Each 10 metres of descent increases the pressure by one atmosphere.

[10] The letter G is used for the Gravitation constant.

experience an apparent loss of weight—astronauts are trained in this environment to handle weightlessness.

Positive Gs can cause several problems for a pilot:

- Blood will tend to be pulled downwards, away from the brain causing Stagnant Hypoxia—see page 33. This initially affects vision as insufficient blood reaches the eyes and can result in unconsciousness. An apparent acceleration of about 4.5g is enough for an average pilot to become unconscious.
- Arms can become too heavy to be moved to the controls.

Negative Gs can also cause problems:

- A condition known as red-out can occur. Common wisdom was that this was caused by excess blood moving up and into the eyes. This is now considered to be physiologically impossible and the effect is believed to be caused by the lower eye-lid, which has no muscles to hold it down, moving up and over the eye ball, exposing the blood vessels inside it. In effect, the affected person is looking at the inside of the lower eye-lid. Whatever the explanation, vision can be seriously affected.
- The increase in blood pressure in the brain as blood moves upwards can cause intense pain, incapacitating the pilot.

Note that "Positive Gs" occur (for the airframe[11] as well as the pilot) in a banked turn, the steeper the turn, the greater the increase in apparent weight—see section 9.7 on page 192.

2.5 Airsickness

Airsickness is a form of motion sickness that affects between 30% and 40% of student pilots at some time during their flight training.

Motion sickness is believed to be caused by conflicts between stimuli from the eyes and the vestibular system:[12] one sense organ tells the body one thing while the other sense organ tells the body something different. Such conflict can happen, for example, in an IMAX cinema when the visual system tells the body it is being rocked on the sea, while the vestibular system is detecting no such movement. This can also occur in an aircraft simulator. Similarly, if you are sitting in a moving car looking down at a book, your eyes may tell you that there is no motion while your vestibular system detects motion.

[11] Where it is known as "Load Factor"

[12] See section 2.11.3 for details of the body's vestibular system

Airsickness is more common in women than in men, and in young children more than in older people. Adults over the age of 50 rarely suffer from motion sickness. It is also more common amongst people of various ancestries.[13] Airsickness can also become a conditioned reflex—people who have previously been airsick in a small aircraft sometimes suffer from it as they walk across the tarmac towards an aircraft!

Airsickness progresses through various stages from paleness of the face, through an increased flow of saliva, to a cold sweat. Eventually the patient will develop a headache, become nauseated and start to vomit.

Generally, over-the-counter medicines for treating motion sickness should *not* be used by pilots as they have been shown to reduce decision-making abilities. Instead airsickness can be mitigated by:

- keeping the cabin cool and having cool air blow over the potential sufferer,
- avoiding the intake of dairy products, high-sodium foods and foods high in thiamin (e.g., sunflower seeds, bluefin tuna) before the flight,
- having the potential sufferer drink or chew ginger before the flight,
- re-assuring the potential sufferer to reduce his or her anxieties and fears and
- flying at an altitude where turbulence is less.

Anecdote 11 *I have found it useful in a small aircraft to allow front-seat passengers who are feeling air sick to take the controls. This reconnects the visual and vestibular cues and seems to reduce the problem.*

2.6 Pregnancy

Section 404.06 of the CARs states that:

> . . . no holder of a permit, licence or rating shall exercise the privileges of the permit, licence or rating if . . . one of the following circumstances exists and could impair the holder's ability to exercise those privileges safely:
>
> . . . (c) the holder has entered the thirtieth week of pregnancy, unless the medical certificate is issued in connection with an air traffic controller licence, in which case the holder may exercise the privileges

[13] See, for example, *Motion Sickness and Differential Susceptibility* by Stern and Koch in "Current Directions in Psychological Science", 5

of the permit, licence or rating until the onset of labour; or

(d) the holder has given birth in the preceding six weeks.

There are several possible implications of flying on a pregnant pilot or her unborn baby:

- During the first six months of a pregnancy there is an increased likelihood of fainting due to low blood pressure, and a decreased tolerance to increased gravitational forces (see *Positive and Negative "G"* on page 40).
- After the fifth month, a pregnant pilot and her baby may become vulnerable to seat-belt injury.
- Cosmic radiation may affect the unborn child. Typically, cosmic radiation exposure for airline pilots in North America ranges from 3 to 5 millisieverts[14] per year (although solar flares can increase this). This is lower than the occupational limit of 20 millisieverts per year (5-year average) that the International Commission on Radiological Protection (ICRP) recommends for a non-pregnant adult. The ICRP recommends that once a woman learns she is pregnant, her occupational exposure to ionizing radiation should not exceed 1 millisievert for the remainder of the pregnancy. Further, the exposure of the unborn child should not exceed 0.5 millisievert in any month. For a long-haul pilot it is possible that this level would be exceeded.

2.7 Body Rhythms/Jet Lag

A human body has a natural rhythm known as the circadian[15] rhythm. The rhythm is linked to the light-dark cycle, although the rhythms of animals kept in total darkness for extended periods move away from the standard 24 hour cycle.

Many body functions are subject to the circadian rhythm: core body temperature, for example, is at its lowest between 03:00 and 04:00 and highest in the late afternoon. When the core body temperature is low, a pilot is less alert and less adrenaline is secreted—the substance a pilot needs to react to a sudden emergency.

Jet lag occurs when a pilot flies across time zones. This upsets the circadian rhythm and can cause digestive upsets, constipation and hunger at inappropriate times. The direction of travel affects the severity of jet lag—it is easier to cope when flying westwards rather than eastwards. In flying westward, the circadian rhythm is temporarily lengthened and body rhythms can extend to a period of about 27 hours and thereby catch up.

There is no medically proven technique for countering jet lag, although there are rules of thumb: undertake physical exercise during lay-overs, avoid alcohol and coffee as they are diuretics, avoid dehydration by drinking lots of water, eat meals high in carbohydrate, and use blindfolds to sleep.

2.8 Sleep/Fatigue

As with stress (see page 15), mental and physical fatigue come in two forms:

1. *Acute Fatigue.* This is a short-term phenomenon, normally caused by a recent high workload, possibly aggravated by hypoglycemia (low blood sugar—see page 37) or mild hypoxia.

2. *Chronic Fatigue.* This is a long-term phenomenon caused by an extended period of lack of sleep. It is a dangerous *precondition* for you making an error and invoking an incident—don't fly if you are suffering from chronic fatigue.

Fatigue tends to produce "tunnel vision" in a pilot: a focus on just one or two things to the exclusion of others. This causes missed incoming radio calls, descents through an assigned altitude, VOR radials entered incorrectly and other careless mistakes. If you do find yourself fatigued during flight, keep busy: recalculate your fuel burn, recalculate your estimated time of arrival, concentrate on very accurate navigation, etc. If you have another crew member then ask for your activities to be double-checked. In a light aircraft, even a passenger can be useful in reading checklists, confirming radio frequencies and carrying out other routine tasks to ensure that you have not made a mistake.

A 1994 study, reported by Sidney Dekker, analysed crew-related aviation accidents and found that flight crews that had been awake for an average of 13 hours made significantly more errors, especially procedural and tactical decision errors, than crews that had been awake for an average of about five hours. The time two hours after the crew had gone to bed on the previous day was found to be particularly dangerous.

Sleep is the natural remedy for fatigue, particularly physical fatigue. As illustrated in figure 2.7, a period of sleep follows a distinct pattern:

- For five or ten minutes there is a transition when the electrical signals in the brain slow down.

[14] The sievert (Sv) reflects the biological rather than the physical aspects of radiation. It is named after Rolf Sievert, a Swedish medical physicist who worked on the biological effects of radiation.

[15] From the Latin *circa* meaning "around" and *diem* meaning "day".

- The body then slides into a period known as stage two sleep where the person is still aware of what is going on around.
- The body then moves into stage 3 and 4 sleep where slow wave sleep (SWS) occurs: this is the deep and restful sleep that overcomes fatigue.
- Periodically during SWS, the brain's electrical signals become jagged and the eye balls move continuously. These periods are known as rapid eye movement (REM) sleep and it is believed that this is when the person is dreaming. Being awoken during REM sleep can cause disorientation and confusion.

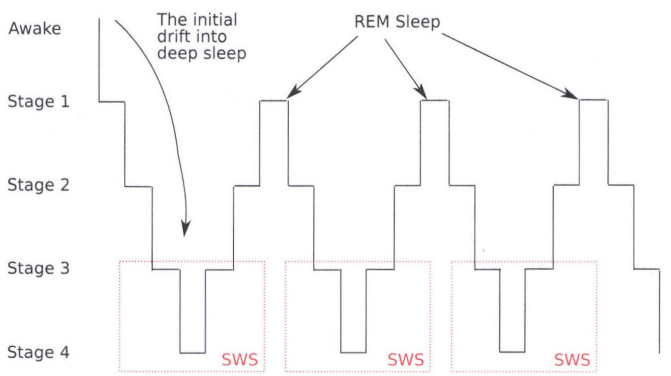

Figure 2.7: The General Pattern of Sleep

The practice of taking short naps is sometimes recommended for pilots (see, for example, the recommendations of the NASA Fatigue Countermeasures Programme[16]). There are, however, negative effects to napping for fixed durations. Awakening at a fixed time means that the person could be in SWS or REM sleep. The end of a nap might then invoke the disorientation and headaches that can accompany awakening out of SWS and the visual hallucinations that can arise from awakening out of REM sleep.

Many aircraft incidents have been attributed to a fatigued crew. One example was the Boeing 747 that crashed on takeoff at Halifax, Nova Scotia on 14th October 2004. The crash occurred because the crew entered wrong information into the software used to calculate the takeoff speeds. The section of the Transportation Safety Board's (TSB) report covering *Findings as to causes and contributing factors* includes:

> Crew fatigue likely increased the probability of error during calculation of the takeoff performance data, and degraded the flight crew's ability to detect this error.

[16]For example, FAA report DOT/FAA/AM-11/10

> Crew fatigue, combined with the dark takeoff environment, likely contributed to a loss of situational awareness during the takeoff roll. Consequently, the crew did not recognize the inadequate takeoff performance until the aircraft was beyond the point where the takeoff could be safely conducted or safely abandoned.

2.9 Anæsthetics

Following an operation that requires spinal or general anæsthesia you should not fly until your aviation medical examiner passes you as fit.

Following local anæsthesia for minor operations and dental work, wait until the effect of the anæsthetic has worn off. After larger operations (such as the removal of several wisdom teeth), wait at least 24 hours before flying.

2.10 Blood Donations

The Airmanship (AIR) section of the AIM states:

> In a completely healthy individual the fluid reduction caused by donating one unit of blood is replaced within several hours. In some people, however, the loss of blood causes disturbances to the circulation which may last for several days. While the effects at ground level are minimal, flying during this period may entail a risk. Generally, active pilots should not donate blood, but if blood has been donated they should not fly for at least 48 hours.

2.11 Disorientation & Illusions

Illusions occur when the body's sense organs send confusing signals to the brain, disorienting the pilot. In Reason's model, disorientation is a *precondition* for the pilot to make an error.

The brain determines the orientation of the body from a number of sense organs, each of which can be confused:

- The eyes—see section 2.11.1
- The kinesthetic system that informs the brain of body orientation—see section 2.11.2.
- The vestibular system that tells the brain of changes in orientation—see section 2.11.3.

2.11.1 Visual Illusions

Vectional Illusions

Vectional illusions are visual illusions caused by relative motion. For example, it is the illusion you have of moving in the opposite direction when sitting in a train in a station next to a train that starts moving.

The most common vectional illusions in flight are those caused by wind drift when flying close to the ground. Imagine flying into a strong headwind and then making a perfect rate-one 180° turn to the right and flying off downwind as illustrated in figure 2.8.

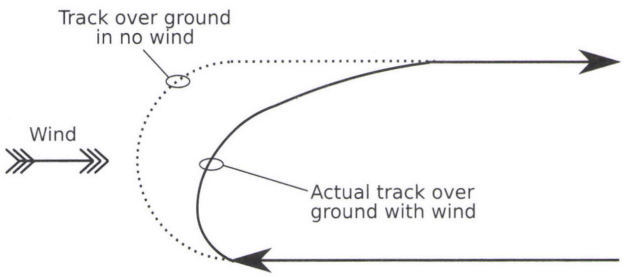

Figure 2.8: Track over the Ground in a Downwind Turn

As long as you do not look out of the window, there should be no problem with this turn. The aircraft is flying in a mass of air and it happens that the mass of air is travelling across the ground. The aircraft, of course, has no idea that the air is moving across the ground. The problem arises if the aircraft is at low altitude and you look out of the window at the ground. The immediate vectional illusion is that the aircraft is slipping since its track across the ground is not circular. For every imaginary problem there is an unnecessary solution and, in trying to correct this situation, it is possible that you will stall the aircraft. When making turns at low altitude, anticipate vectional illusions and use the instruments rather than ground reference to ensure that you are turning cleanly.

Autokinesis Illusions

This visual illusion happens at night and causes isolated lights fixed to towers on the ground to appear to move. In fact the eyes are losing their fixation of the light, drifting off and then jumping back. This gives the illusion that the light is moving and pilots have been known to change course to avoid such moving lights. To overcome this illusion, consciously look away and then back again.

Runway Illusions

Most pilots fly regularly from one or two aerodromes and the runways at those aerodromes have certain characteristics. Over time, the visual image of those runways when flying a standard approach becomes second nature. When flying an approach into an aerodrome with a different type of runway, the eyes can deceive the brain into thinking that the aircraft is too low or too high.

Exam Hint 2 *As examination hint 1 explains, it is generally very difficult to set multiple choice questions on human factors. One area for which it is very easy to set such questions is the topic of runway illusions. Expect a question on these.*

Figure 2.9 lists the main runway illusions and figure 2.10 illustrates one of those illusions: the different views of upsloping and downsloping runways when on a normal 3° glideslope.

Condition	Illusion	Resulting approach is ...
Narrow Runway	Too high	too low
Wide Runway	Too low	too high
Upsloping Runway	Too high	too low
Downsloping Runway	Too low	too high
Poorly Lit Runway	Too high	too low
Well Lit Runway	Too low, too close	too high
Featureless terrain	Too high	too low

Figure 2.9: Runway Illusions

If you were landing on the runway to the left in figure 2.10, not aware before starting the approach that the runway sloped upwards, you would have the illusion of being too high and you might increase your rate of descent, perhaps landing short of the runway. Similarly, when landing on the runway to the right in figure 2.10, you would feel too low and climb, landing a long way down the runway.

Assume, for example, that you normally fly from an airport with a runway 300 ft wide that has lots of trees on final approach. You are used to seeing the runway appear a certain size in the windscreen as you descend on final approach, and out of the corner of your eye you will be used to the peripheral vision of trees flashing by below. Now assume that you are going to land at an aerodrome with a runway that is 60 ft wide and where the final approach is over water. Even if your approach is perfect, the runway will appear substantially narrower than normal and there will be no sensation of the trees

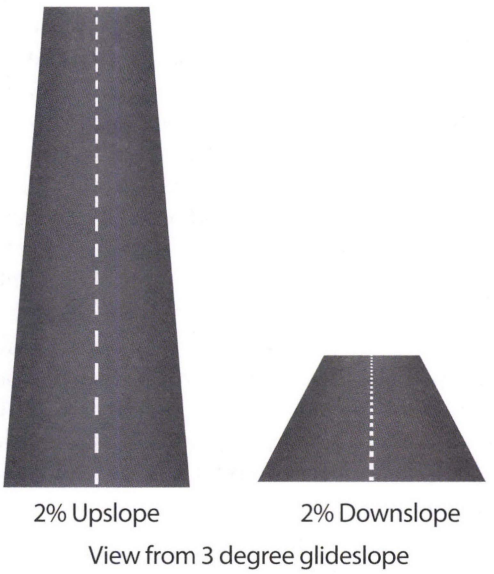

Figure 2.10: Different Runway Views

flashing by beneath you. At your normal airport both of these sensations would occur if you were very high: the runway would look narrower and the trees would be less obvious. You therefore receive the illusion that you are too high and, disoriented, you descend to get onto the "proper" glideslope. This results in you making your approach too low. To avoid illusions of this type:

- Accept that they are real. Student pilots are often used to flying into small airports that have relatively narrow runways. When they fly into an International Airport, the student will often land 4,000 ft down the wide runway. If the small field runway is only 3,000 ft long, the student has overflown more runway than the total length of the one on which he is used to land!
- Read the CFS or Canada Air Pilot to determine the width (and slope) of the runway you will be using. Then anticipate the illusion that will occur and consciously compensate for it.
- Never hesitate to overshoot and go around if things do not feel right on approach.

Exam Hint 3 *You don't need to learn the conditions in figure 2.9—they can all be deduced fairly simply. Faced, for example, with a runway narrower than the one with which you're familiar, ask yourself: "When would my normal runway look like that?" The answer is that your normal runway would look narrow if you were too high. The illusion caused by a narrow runway is therefore that you are too high. How might you unconsciously try to correct being too high? You would fly lower!*

Exercise 10 *A pilot is used to flying from an international airport where the runway is 150 ft wide. When flying into an aerodrome where the runway is only 50 ft wide, for which illusion should the pilot prepare?*

2.11.2 Kinesthetic Illusions

Your body is used to living on the surface of the earth where gravity acts downwards. For example, when you are standing the brain gets cues from the tension in various muscles to help determine the body's orientation. When flying, such cues are no longer helpful.

In a perfectly co-ordinated banked turn, for example, your effective weight no longer acts directly downwards, rather it acts through the seat in which you're sitting. If visual and other cues are missing because you are in IMC, this can mislead the brain into thinking that you are flying straight and level.

At the top of a loop a blindfolded pilot would feel gravity (weight) appearing to act vertically upwards—directly away from the earth.

2.11.3 Vestibular Illusions

One sense organ particularly important for the brain to determine movement, and for the body to retain balance is the Vestibular System. This consists of:

1. Three "semi-circular canals" containing liquid in each inner ear. These are fixed almost at right-angles to each other as illustrated in figures 2.5 and 2.11, and detect motion in what a pilot would term roll, pitch and yaw.

   For example, when a person leans forward, the fluid flows around one or more of the semi-circular canals and bends the hairs in the liquid. The bending of the hairs is detected by the brain and interpreted as movement around the appropriate axis.

2. Two organs in each ear sensitive to accelerations in the horizontal and vertical planes. The acceleration is detected by the movement of small hairs topped with stones of calcium protruding into the fluid stream. As with the semi-circular canals, bending of the hairs is detected by the brain and interpreted as acceleration.

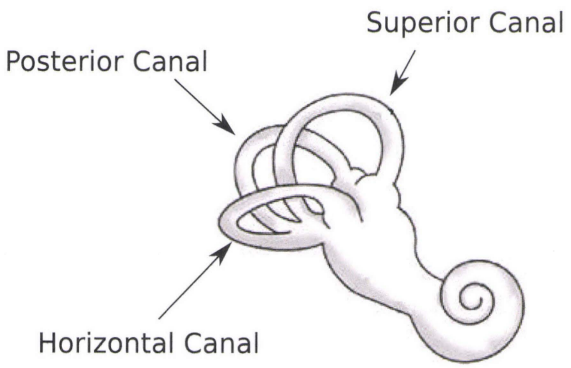

Figure 2.11: Semicircular Canals

The vestibular system can be easily fooled. Place a blindfolded "volunteer" in a chair that can be smoothly rotated and start the chair rotating clockwise. The volunteer will instantly detect the rotation because the fluid in the ears does not immediately start to move, causing the hairs to bend. However, continue the rotation and eventually the fluid will catch up with the canal. The hair will then return to its upright position and the brain will detect no movement. Without the visual cues, the volunteer will believe that he or she is still. Now slow the rotation slightly and the fluid will continue flowing for a few moments, bending the hairs in the opposite direction. The volunteer will feel that he or she is now being rotated in an anticlockwise direction. Bringing the chair to rest, the volunteer will sense a strong anticlockwise rotation.

When flying in cloud where there are no visual cues, these illusions are particularly dangerous. Particular manifestations of vestibular illusions include the following:

The Coriolis Phenomenon. This occurs when a pilot in IMC makes a rapid head movement, particularly in the opposite direction to which the aircraft is turning. The signals from the vestibular system give the impression of violent tumbling and in some cases, the whole instrument panel appears to be rotating. This is very dangerous; therefore pilots are strongly advised to avoid sudden head movements when in IMC.

The Graveyard Spiral. This is the condition described so graphically in Appendix E on page 351. It occurs when the semi-circular canals are misleading a pilot who is flying in cloud by indicating a turn when none exists, or no turn where one does exist. This is the situation described above with the rotating chair.

The Somatogravic Illusion. This is also known as the "Black-Hole Effect". It occurs when taking off from a runway at night into an unlit area of countryside. The organs in the ear are unable to distinguish between a pitched-up attitude and an acceleration: the head being tipped backwards and the head being level but accelerating moves the hairs towards the back of the head in the same way.[17] Unfortunately a normal aircraft attitude indicator has the same weakness. As the aircraft starts to climb, if the pilot fixates on the attitude indicator to confirm that the aircraft is climbing, the confusion between acceleration and attitude can be deadly. Initially the aircraft may start to climb but, perhaps because of a distraction, the pilot allows the nose of the aircraft to drop slightly. This causes the aircraft to accelerate, and the acceleration is registered both by the pilot's body and the attitude indicator as a pitch-up, climbing attitude. Seeing that the "climb" is too steep, the pilot pushes the nose forward. The aircraft again accelerates and a pitched-up attitude again registers on the body and the attitude indicator. This continues until the aircraft flies into the ground some miles off the end of the runway. The *defence* against this is, of course, to use all of the instruments available and not just the attitude indicator.

An example of the black-hole effect occurred on 30th September 2005 when a Piper Navajo left Kashechewan, Ontario at 21:30 local time on a night VFR flight to Moosonee. The aircraft became airborne approximately halfway down the runway and the crew lost sight of the runway lights and any visual reference to the ground shortly afterwards. The captain selected the landing gear up, and, at 200 ft AGL, the first officer selected the flaps up, after which the captain set climb power. There was a slight drop in manifold pressure on the left engine, and the captain was readjusting the power when the aircraft struck the ground. The Transportation Safety Board (TSB) report includes:

> *During the night VFR departure into "black hole" conditions, the flight crew likely experienced a somatogravic illusion, giving them a false climb sensation. This likely contributed to the captain allowing the aircraft to descend into the ground.*

A similar incident happened on 29th October 2014 when a Shorts 360 departed runway 28 at the Princess Juliana International Airport, Sint Maarten. This was an unusual departure runway. From the normal runway, the aircraft would climb

[17] This illusion is used to good effect in full motion simulators where tipping the simulator backwards while keeping the visual image fixed gives a very realistic effect of acceleration.

out over the lights of the town. From runway 28 the climb-out was directly over the sea where there were no lights. The crew suffered a somatogravic illusion immediately after takeoff and landed in the sea only 0.8 miles from the airport.

Such incidents related to the black-hole effect have encouraged the TSB to recommend that the definition of when VFR flight is allowed should be clarified—see section 14.6.8 on page 322.

The Leans.[18] This is a mild (but confusing) version of the graveyard spiral. The semi-circular canals do not respond to roll rates of less than about 3° per second. Imagine a pilot glancing down at a map and a wing dropping to 15% over 5 or 6 seconds. When the pilot looks up, the instruments indicate a turn but the body does not. In correcting the turn, the pilot is likely to roll at more than 3° per second and the semi-circular canals will detect this as a roll in the opposite direction. This is very common in IFR flight without an autopilot and is usually more comical than alarming for a trained pilot.

2.11.4 Disorientation

Any of the illusions described above can lead to serious disorientation, a major cause of aviation accidents. For a VFR pilot, the best way of avoiding disorientation is, of course, to avoid losing visual cues—i.e., avoid entering cloud. However, this is a counsel of perfection. All VFR pilots will, from time-to-time, experience decreasing visibility and lose visual cues.

The steps to take should include the following:

- Be aware that the situation you are entering is likely to cause illusions and disorientation. Brief yourself on the types of illusion you will meet.
- Carry out regular simulator training where the instructor can put the aircraft into a spin or graveyard spiral, and you can interpret the instruments and recover. This practice could save your life one day.
- Do not trust your senses.
- Believe and follow the instruments.

[18] There is also a visual illusion called "the leans". This occurs when a pilot, particularly at night, levels the wings against the top of a sloping cloud-bank, believing it to be the horizon. This visual illusion is not related to the vestibular illusion described here.

2.12 Answers to Exercises

This section provides some answers to the examples in this chapter.

Exercise 9

This question is harder than would be given on a Transport Canada examination. The answer is calculated from equation 2.1 as follows:

$$\begin{aligned} T_{wc} &= 13.12 + 0.6215T_a - \\ &\quad (11.37 - 0.3965T_a)\left(\frac{V}{0.53}\right)^{0.16} \\ &= 13.12 + 0.6215 \times (-20) - \\ &\quad (11.37 - 0.3965 \times (-20))\left(\frac{19}{0.53}\right)^{0.16} \\ &= 13.12 - 12.43 - 19.3\,(35.8)^{0.16} \\ &= 13.12 - 12.43 - 19.3 \times 1.773 \\ &= -33.5 \end{aligned}$$

The apparent temperature will be −33.5°C.

Exercise 10

On a correct 3° descent to the smaller runway, it would look narrower than usual. The wide runway to which the pilot was used would look like that if the approach were too high. The pilot will therefore feel too high and, unless anticipating the illusion, could descend prematurely and become too low.

Chapter 3

Aviation Measurements

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Various units of measurement are used throughout this book: pressure measured in inches of mercury or millibars, power measured in horsepower or watts, etc. Rather than describe these repeatedly in the chapters which follow, they are gathered together here for convenience.

It must be said that the choice of units used in the aviation industry in North America can be justified only by an appeal to history. It is unlikely that anyone setting out today to select a system of units would propose those currently in use.

3.1 Units Named After People

Many units, such as the newton, amp, ohm, coulomb, joule, pascal, kelvin and many others are named after particular people. When one of these units is used in its abbreviated form (N), it must be written with a capital letter, but when the full name of the unit is written out (newton) it must be written with a lower-case letter. This may not sound sensible, but it is true for all units except, for some reason, Celsius: see `http://www.npl.co.uk/reference/measurement-units/si-conventions/`.

3.2 Time

The 24 hour clock is well known to most Canadians. Midnight is 00:00, midday is 12:00 and one minute before midnight is 23:59.

Times can be written in various ways and it is essential to be able to convert between them. This is simple using an aviation calculator as these have functions to switch between the "hours, minutes, seconds" (e.g., 23 hrs 30 mins) and the "decimal hours" (e.g., 23.5 hours) formats.

Exercise 11 *Convert 3 hours, 6 minutes and 25 seconds to decimal hours.*

Possible answers to the exercises are given at the end of the chapter, starting on page 53.

3.3 Angles

In a manner very similar to time, angles are measured in degrees, minutes and seconds. There are 60 seconds in a minute and 60 minutes in a degree.

As with time, it is important to be able to convert between formats because different navigation applications use different formats when entering latitudes and longitudes.

Exercise 12 *Convert 3 degrees, 6 minutes and 25 seconds to decimal degrees.*

3.4 Temperature

The Celsius temperature scale is a centigrade scale; that is, it has 100 degrees between the freezing and boiling points of water.[1] A temperature of 23 degrees Celsius is written as 23°C. The Celsius scale is used in all aviation

[1] When Anders Celsius first proposed the scale he set 0 degrees as the boiling point of water and 100 degrees as the melting point of ice. This was reversed in 1743.

weather reports. This scale defines 0°C to be the temperature at which ice melts into water and 100°C to be the temperature at which water boils at standard atmospheric pressure. At lower atmospheric pressures water boils at a lower temperature[2] and at higher atmospheric pressures it boils at a higher temperature.

Note that the definition of 0°C is given as the temperature at which ice melts, not the temperature at which water freezes. It is more difficult to define the temperature at which water freezes: super-cooled water droplets (i.e., liquid water at temperatures below 0°C) are common and particularly dangerous for aircraft.

In the USA, for non-aviation purposes, the Fahrenheit scale is used. This defines the melting point of ice to be 32°F and the boiling point of water to be 212°F. Conversion between the units is as follows:

Fahrenheit to Celsius Temperature: subtract 32, multiply by 5 and divide by 9.

Celsius to Fahrenheit Temperature: multiply by 9, divide by 5 and add 32.

Celsius to Fahrenheit Degrees: multiply by 9 and divide by 5.

Fahrenheit to Celsius Degrees: multiply by 5 and divide by 9.

Note the significant difference between *degrees Celsius* and *Celsius degrees*. If the temperature is 10°C then it is 50°F. If the temperature *rises* 10 Celsius degrees then it rises 18 Fahrenheit degrees (not 50).

For scientific work, temperature is measured in kelvins (abbreviated as K). This is also a centigrade scale, but the melting point of ice is 273.15K and the boiling point of water is 373.15K. Note that there is no degree sign—it is not "273.15 degrees kelvin", it is "273.15 kelvins".

Exercise 13 *A friend from the USA tells you that the current temperature is 80°F. What is this in Celsius?*

Exercise 14 *While waiting at an airport in the USA you learn that the temperature is forecast to increase by 15 Fahrenheit degrees over the next hour. It is currently 8°C. What is the expected temperature in an hour's time?*

[2]This is why you need a pressure cooker to make a good cup of tea at the top of a mountain.

3.5 Distance

Distances in North American aviation are measured in three units:

1. feet for vertical distances and relatively short horizontal distances, such as the length of a runway.
2. nautical miles for longer horizontal distances. A nautical mile is the distance between two lines of latitude one minute apart.
3. statute (normal) miles for expressing visibility.

Exercise 15 *Midland (Huronia) airport is located at N44 41 W79 56. Arnstein is located at N45 56 W79 56. How far is it from Midland to Arnstein?*

3.6 Speed

The speed of an aircraft is measured vertically in feet per minute and horizontally in knots. A knot is one nautical mile per hour.

One exception to this is that glider (sailplane) pilots tend to measure their vertical speed in knots: one knot is almost exactly 100 feet per minute. So a glider pilot may say, "I am climbing at 4 knots" when climbing at 400 feet per minute.

Exercise 16 *Given the answer to exercise 15, how long would it take to fly from Midland to Arnstein at an average speed of 90 knots?*

3.7 Mass

Bodies have mass, measured in kg or pounds. Unlike weight, the mass of a body does not depend on where the body is. A person with a mass of 100 kg on earth has a mass of 100 kg when on the moon, and a mass of 100 kg when in deep space.

A body's mass can be thought of as a measure of how hard it would be to stop it if it were coming towards you. A 2,000 kg rock would crush you on earth if it came towards you at, say 5 knots, and forced you against a wall. In space, the rock's mass would still be 2,000 kg and it would still crush you against the wall, even though its weight would be zero.

3.8 Force

We are all aware of forces that act upon us and that we impose on other things. As you sit on a hard chair, you can feel it imposing a force upward on you. At the same time you are exerting the same force down on the chair, and if the chair is not strong enough to handle this force, it will break.

Weight is a force; it is the gravitational force acting on a body.

In science, the magnitude of a force is measured in newtons; in North American aviation it is measured in pounds-force. One newton is approximately 0.224808943871 pounds-force. When people speak loosely about the weight of an aircraft, they will often shorten "pounds-force" to "pounds" and say, "the gross weight of a Cessna 172M is 2,300 lbs." Strictly this is incorrect, but it is common usage.

On the surface of the earth, a person's weight (in newtons) can be calculated by multiplying her mass (in kg) by 9.8, the acceleration of gravity in metres per second per second. On the moon, her mass would be unchanged, but her weight would be less because the moon's gravity is less strong than the earth's. On the moon her weight would be found by multiplying her mass by 1.6 rather than 9.8.

Exercise 17 *Jane has a mass of 55 kg. What is her weight when she is on the earth? What would her weight be if she were on the moon?*

3.9 Pressure

Meteorologists use a confusing set of pressure units. Pressure is a measure of how much force is being applied over what area. So a small force applied over a large area might exert the same pressure as a large force exerted over a small area. A stiletto heel on a shoe, for example, typically exerts a relatively small force on the floor (part of the weight of the person wearing the shoe) but the area is small and so the pressure can be very high—often causing damage to wooden floors. On the other hand, an elephant walking over the same floor is unlikely to do damage: the force is much greater, but the elephant's feet are much larger and so the pressure is less.

The internationally agreed unit of pressure is the pascal.

One pascal is equivalent to one newton (force) acting on one square metre (area).

Exercise 18 *You weigh 1 kN and the soles of your shoes can be assumed to be rectangles 0.3m by 0.1m. What pressure do you exert on the floor when you stand still?*

If everything were measured in pascals, it would be easy. However, as exercise 18 shows, pressures in pascals can be quite large numbers. Rather than using the approved prefixes (kilo, Mega, etc.) meteorologists use the *hecto* prefix—meaning 100. The pressure you exert on the ground as calculated in example 18 could be expressed as 166.67 hectopascals. The hecto- prefix is rarely used outside meteorology except in the measurement of land area where *hectare* is sometimes used to mean 100 ares.[3] There are groups dedicated to banning the use of the hecto prefix in meteorology but it remains in prevalent use.

One reason that the hectopascal has persisted is that it is equivalent to a millibar, the *bar* being another unit of pressure often used in meteorology.

For aviation in North America (although not elsewhere in the world), there is one further unit of pressure: inches of mercury. The pressure of the atmosphere at sea level varies from day to day, but can hold up a column of mercury about 30 inches high; see figure 3.1. The height of this column at a particular time can be taken as a measurement of the atmospheric pressure. In a "standard atmosphere" the column of mercury is 29.9212725 inches high. This allows us to talk about high pressure days (where the atmosphere can hold up a higher column) and low pressure days.

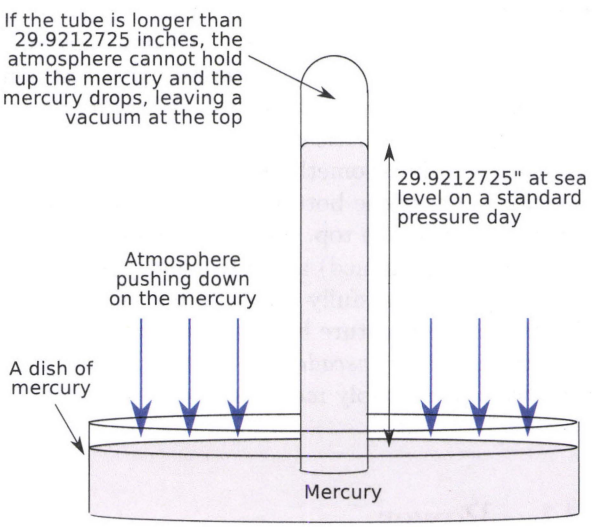

Figure 3.1: A Representation of 29.9212725″ of Mercury

[3] Although horizontal visibility on an aviation surface analysis chart is given in hectometres!

Aviation weather reports (METARs—see section 5.3.2 on page 96) report the sea-level atmospheric pressure in centi-inches of mercury (e.g., 29.92″ is represented as 2992) and in a strange, truncated form of millipascals (e.g., 1004.0 hectopascals is written 040—the initial 10 being dropped and the hectopascals being converted to millipascals).

3.10 Work & Energy

When you apply a force to something, it may move. You can apply a force to depress the key on the keyboard or carry a brick up a ladder. In each case you are doing *work*. Work is what happens when a force moves something. As a result of having work done on it, that thing gains *energy*. If you do work to lift a brick to the top of the ladder, then that brick has more energy—potential energy. If you do work to make a car move more quickly, then that car has more energy—kinetic energy. If you do work (e.g., rubbing two sticks together) to heat some water, then that water has more energy—thermal energy. Both energy and work are measured in joules or calories. Be careful with calories because the amount of energy in food is often expressed in calories when what is meant is kilocalories.

The important fact about energy is that (excluding relativistic effects!) it can neither be created nor destroyed—it can only be converted from one form to another. This is the principle of conservation of energy. As an example, water flowing in a river at the top of a waterfall has potential energy (because it's high up) and kinetic energy (because it's moving). As it flows over the waterfall it loses potential energy (it's now not so high up) which has to be converted to another type of energy. In fact it becomes kinetic energy—it's now moving faster. At the bottom of the waterfall it has lost some of its potential energy and, if the river is flowing more slowly, some of its kinetic energy. This energy must have been converted into something else, into heat in fact—the water at the bottom of the waterfall is warmer than the water at the top. James Prescott Joule (after whom the unit is named) actually spent part of his honeymoon unsuccessfully trying to measure the difference in temperature between the water at the top and bottom of the *Cascade de Sallanches* waterfall. Brides were presumably more long-suffering in 1847 than today.

3.11 Power

Power is the rate at which work is done. Carrying a brick to the top of a ladder always requires the same amount of work, but if you do it more quickly, then you expend more power.

Power is measured in watts or, in some parts of aviation, in horsepower—radio, as well as electric motors, tend to be measured in watts, but engine power of older aircraft in horsepower. If you do one joule of work per second then you are expending 1 watt. The conversion between watts and horsepower is somewhat variable because there are various definitions of horsepower but, roughly, one watt is 0.001341 horsepower.

3.12 Electrical Units

Several sections in this book refer to the electrical units volts, amps and ohms.

Under certain conditions an electrical current can flow through a conductor. The electricity is carried by the movement of sub-atomic particles called *electrons* and the amount of electricity (number of electrons) passing a point in a conductor every second is measured in **amperes** (or amps). One amp is said to be flowing if 6,241,509,629,152,650,000 electrons flow past every second.

Before current will flow, there has to be a potential difference between the two ends of the conductor, effectively a slope for the electrons to flow down. The difference in "height" between the top and the bottom of the slope is measured in **volts.**

Electrical current is measured with an *ammeter* placed into the circuit so that the current flows through it. Potential difference is measured with a *voltmeter* that is placed across the two points between which the potential difference is required.

From whatever material a conductor is made, it will resist the flow of electricity to some extent. Copper has a very low resistance to electrical flow and wood has a much higher resistance. The resistance of a particular substance is measured in **ohms**.

If a large voltage is placed across a conductor with a low resistance then a large current will flow. If a small voltage is placed across a conductor with a high resistance then a small current will flow.

3.13 Common Units

Figure 3.2 lists some of the measurement units used in aviation in North America, together with the more common, everyday units.

Dimension	Non-Aviation Unit	North American Aviation Unit	Conversion
Runway Length	metres	feet	1 m ≈ 3.28 ft
Flight Distance	kilometres	nautical miles	1 km ≈ 0.54 nm
Visibility	kilometres	statute miles	1 km ≈ 0.6214 sm
Horizontal Speed	kilometres/hour	knots	1 km/hr ≈ 0.54 kts
Vertical Speed	metres/second	feet/minute	1 m/s ≈ 196.8 ft/min
		knots	1 m/s ≈ 1.944 kts
Altitude	metres	feet	1 m ≈ 3.28 ft
Radio Power	watts	watts	
Engine Power	watts	horsepower	1 kW ≈ 1.341 HP
Tire Pressures	pascals	pounds/sq inch	1 Pa ≈ 0.068 lb/sq in
Atmospheric Pressure	millibar	inches mercury	1 mb ≈ 0.0295″ Hg
		hectopascals	1 mb = 1 hP
Weight	newtons	pounds-force	1 N ≈ 0.2248 lb-force
Temperature	degrees Celsius	degrees Celsius	
Temperature Difference	Celsius degrees	Celsius degrees	

Figure 3.2: North American Aviation Units

3.14 Answers to Exercises

This section contains possible answers to the exercises in this chapter.

Exercise 11

Find the button on your calculator that allows you to enter time as hours, minutes and seconds. On the CX-2, for example, it is marked with a colon (:).

- On a CX-2 enter 3 : 6 : 25
- press SECOND-FUNCTION HMS→H
- read 3.10694

3 hours, 6 minutes and 25 seconds is 3.10694 hours. You can check this by pressing SECOND-FUNCTION H→HMS and making sure that 3 hours, 6 minutes and 25 seconds is returned.

Exercise 12

This is the same as question 11 and is trivial with an electronic flight calculator but we will do it long-hand, dividing the 6′ by 60 to convert it to degrees and the 25″ by 60 to convert it to minutes, and then by 60 again to convert it to degrees.

$$3°6'25'' = 3 + \frac{6}{60} + \frac{25}{60 \times 60} \text{ deg} = 3.10694°$$

As expected, this is the same answer as that for exercise 11 except that the answer is now in degrees rather than hours.

Exercise 13

Using the rule in the text, you must subtract 32 (giving 48), multiply by 5 (giving 240) and divide by 9 (giving 26.7). The answer is 26.7°C.

Exercise 14

Using the rule in the text, you can calculate the expected temperature rise in Celsius degrees by multiplying by 5 (giving 75) and dividing by 9 (giving 8.3). It is expected that the temperature will increase by 8.3 Celsius degrees. So the expected temperature in an hour is $8 + 8.3 = 16.3$°C.

Exercise 15

The first point to notice is that the longitude of Midland and Arnstein are the same, so Arnstein lies directly north of Midland. The difference in their latitudes is

$45°56' - 44°41' = 1°15'$

which is 75 minutes. As one minute of latitude is one nautical mile, Arnstein lies 75 nautical miles north of Midland.

Exercise 17

Weight can be calculated from mass by multiplying by the acceleration of gravity. On earth this is about 9.8 metres per second per second and on the moon it is about 1.6 metres per second per second. So, on earth Jane weighs $55 \times 9.8 = 539$ newtons. On the moon her mass would be the same, but her weight would be $55 \times 1.6 = 88$ newtons.

Exercise 16

As calculated above, it is 75 nautical miles from Midland to Arnprior. At 100 knots (i.e., 100 nautical miles per hour), it would take $\frac{75}{100} = 0.75$ hours to fly from one to the other. That is, the flight time would be 45 minutes.

Exercise 18

The area of each shoe is $0.3 \times 0.1 = 0.03$ square metres. Since you have two shoes, the total area in contact with the ground is 0.06 square metres. Therefore, you exert a pressure of $\frac{1000}{0.06} \approx 16667$ pascals on the ground: approximately 16.667 kP.

Chapter 4

Meteorology

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4.1 Introduction

Meteorological topics are covered in this book in two parts:

1. What makes weather? How do atmospheric temperature, humidity and pressure combine to produce rain, snow, ice, tornados, thunderstorms, etc.? This topic is covered in this chapter in more depth than is strictly required for the written examination, aiming to provide useful information for every pilot.

2. How do pilots obtain weather information? How are weather reports and forecasts prepared and distributed to pilots? These questions are answered in chapter 5.

There are many excellent books on meteorology for pilots. *Flying the Weather Map* by Richard L Collins records the forecast weather for a number of flights Collins made and compares these with the actual weather he encountered, explaining the differences.

Meteorology is at root a mathematical discipline and many books provide a more mathematical account of meteorology for those pilots who are comfortable with calculus. One such is *Dynamical Meteorology: An Introductory Selection* edited by B.W.Atkinson. This book is now very dated (last published in 1990) but it contains some classic papers. There are also many papers available on the Internet describing the latest mathematical models used in forecasting; see section 5.2.2 on page 95 for keywords useful for finding these papers (e.g., HRRR).

4.1.1 The Challenge

We live at the bottom of a sea of air—the earth's atmosphere. The atmosphere is in a continual state of change as parts of it heat up while other parts cool down, winds blow, clouds form and dissipate, water evaporates and condenses, pressures change, air masses butt against each other. The energy for all this dynamic behaviour comes from the heat of the sun.

It is the role of a meteorologist to predict these changes and foresee the resulting weather. This is an extremely difficult task. Weather Forecasting led to the invention (or discovery) of the mathematical technique known as *Chaos Theory*. In 1961, Edward Lorenz was using a computer to simulate the weather and wanted to repeat a calculation. To save time, he restarted the calculation in the middle by entering the data printed out at that point during the previous run. To his surprise the weather the machine predicted was completely different from that predicted before. Lorenz tracked this down and found that, although the computer worked with 6-digit precision, he had only entered 3-digit numbers (e.g., 3.45 instead of 3.45103). The tiny differences in the starting conditions led to completely different conclusions. This discovery that weather prediction is *very* sensitive to the precise starting conditions, made people realise that, since today's atmospheric conditions cannot be known precisely, it will never be possible to produce accurate forecasts for more than a short time ahead.

This chapter covers some of the techniques likely to be useful when you are predicting the type of weather you will encounter during a flight. To this end it primarily addresses weather systems at the synoptic scale (part or all of a continent), the mesoscale (20 to 20,000 km across) and the microscale (a few kilometres across).

Meteorologists also study phenomena at the planetary scale but these are not generally of interest to a pilot in Canada. However, there is an excellent website (`https://earth.nullschool.net/`) that provides a dynamic picture of the state of the currents in the atmosphere and oceans and I strongly encourage everyone to use this planetary scale resource. Figure 4.1 shows a static image of a small part of the image on the website.

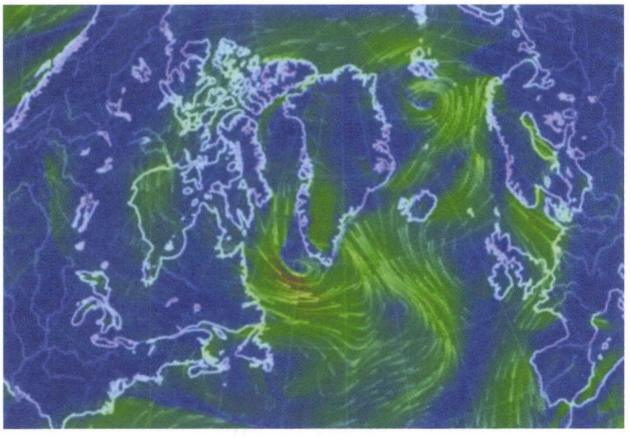

Figure 4.1: Atmospheric Flow

In order to be able to "read" a weather chart you need to understand how the temperature, pressure and moisture profiles of the atmosphere through which you will be flying are likely to change.

4.1.2 Planning a Flight

When planning a flight, it is important to have a strategy for interpreting the weather information. Work from the big picture downwards, and ask yourself:

- what are the large-scale weather-makers, how are they moving, how will they affect the flight?

- how might they have affected airports in the last couple of hours? Can I confirm my understanding by reading the reports from those airports?
- how are they likely to affect the airports along the route of flight? Can this be confirmed from the forecasts for those airports?

You can then have the confidence to ring Flight Services for a briefing knowing that you can engage in a dialogue ("but don't you think that the front might slow down when ...?") rather than just having information thrust at you.

And always remember, no forecast is ever perfect.

4.1.3 Basic Concepts

The Adiabatic Process

There is one concept of major importance throughout the study of meteorology: the behaviour of a gas as it expands and contracts without appreciable heat being lost to, or gained from, the outside world. Such a system is known as an *adiabatic* one.[1] The term "adiabatic" itself is in three parts:

1. 'a' meaning 'not' as in '**a**theist': not a theist
2. 'dia' meaning 'across' as in '**dia**meter'
3. 'batic' meaning 'passing'

The result is that it describes a process where energy does not pass across the boundary of the system.

Anyone who has used a manual bicycle pump to inflate a tire is aware that compressing a gas heats it up: the end of the pump where the air is being compressed gets hot! As explained in section 12.4.4, it is this principle that lies at the heart of the diesel engine: the compression caused by the rising piston causes the temperature of the gas to increase to a point where the fuel ignites.

The opposite effect occurs as well: when a gas expands against an outside pressure, its temperature drops. This is the way in which a refrigerator works: a gas is compressed, cooled and then allowed to expand rapidly. As its pressure decreases, its temperature drops because it loses energy as it does work pushing against the outside air. This principle was first noticed by Louis-Paul Cailletet in 1877 when a container in his laboratory broke, releasing some acetylene under very high pressure. As the gas expanded, it cooled and Cailletet noticed a vapour—the first time acetylene had been liquefied.

[1] In practice, some heat *is* always gained or lost from the surrounding air in most of the processes described in this chapter, but this small amount can often be ignored.

Adiabatic cooling and heating occurs to parcels of air as they rise and sink in the atmosphere and their pressure reduces and increases.

Latent Heat

Latent heat provides the energy for many of nature's greatest meteorological shows. In particular it provides the energy for thunderstorms.

If you take a block of ice at $-10°C$, put a thermometer into it and place it in an oven you will notice the temperature of the block rising. However, once it reaches $0°C$, and the ice starts to melt into water, the temperature remains at $0°$ until the melting is complete. Then it starts to climb again as the water warms up.

During the melting process, energy (heat) is being applied, but the temperature is not changing. This type of heat is called *Latent Heat*. It is the heat required to change the state of something (e.g., from ice to water) without changing its temperature.

A similar phenomenon occurs at the liquid/gas boundary. If you heat water in a kettle, its temperature will rise until it reaches $100°C$. Then, irrespective of the amount of heat you put in, the temperature will remain unchanged until all the water has become steam.

When a gas turns into a liquid or a liquid into a solid, latent heat will be emitted while the temperature remains unchanged.

This means that when water vapour condenses out of the air to form a cloud (i.e., a gas turns into a liquid), the energy that went into vapourising the liquid in the first place is emitted. This is the energy that fuels thunderstorms and many other weather phenomena.

Partial Pressure & Vapour Pressure

In a mixture of gases (such as the atmosphere) the *partial pressure* of each gas is the pressure it would exert on the container if the other gases were removed. If the gases are "perfect" then the total pressure of the mixture is the sum of the partial pressures of each of the constituents: effectively the molecules of the different gases are so far apart that they don't interact with each other.

In meteorology (although not in chemistry), the term *vapour pressure* is used for the partial pressure of water vapour in the atmosphere.

Consider a body of air containing water vapour over an area of liquid water. At a particular temperature, if the number of molecules of water vapour condensing into the liquid water every second is the same as the number of molecules evaporating from the liquid water into the air every second, then the partial pressure of water vapour is called the *saturated vapour pressure*. In this

state the air can be considered "saturated" with moisture: the liquid water underneath is not evaporating and there is no net condensation of the water vapour.

When the water vapour in the air is at its saturated vapour pressure, then any cooling or increase in pressure will cause condensation to occur as rain, mist or dew.

Representing Atmospheric Pressure

See section 3.9 on page 51 for a description of the units used to measure pressure.

The pressure that the atmosphere exerts on the earth varies from place to place and from time to time. Meteorologists produce two types of maps that illustrate this pressure difference:

1. Maps with lines joining all points where the pressure at sea-level is the same. These lines are called *isobars* and appear on charts of various types including the graphical area forecast (section 5.4.1 on page 101) and surface analysis charts (section 5.5.2) In this case the altitude is constant (sea level) and the pressure is indicated by the isobars.

2. Maps with lines joining all points where the altitude is the same for a certain pressure. These lines are called *contours* and appear on the upper-air charts (section 5.5.3). In this case the pressure is constant and the altitude at which that pressure is forecast to occur is indicated by the contours. On a 500 hectopascal chart, for example, the contour line indicates how high you would have to go before the pressure dropped to 500 hectopascals.

Each of these charts has its uses, some things being easier to visualise with isobars and other things with contours. Winds, for example, may be visualised as being caused by gravity pulling an air mass down a slope on an upper-air chart or as being caused by the pressure gradient from a high pressure to low pressure on a surface analysis chart.

In the remainder of this chapter you'll find use of whichever of these representations is simpler for a particular explanation. Most people are more familiar with the isobar representation because these are the maps drawn in newspaper and television weather forecasts. A candidate for the Transport Canada Commercial Pilot written examination needs to be familiar with both.

4.2 The Earth's Atmosphere

4.2.1 Composition & Structure

Anecdote 12 *We often say that we live at the bottom of an ocean of air and I like to provide students with a globe, about 40 cm across, and ask them to indicate how deep that ocean of air is. Often they will place their hands several centimetres above the surface of the globe. In fact, the atmosphere can be thought of as being about 60,000 ft (18 km) deep. On the scale of the globe, that is about 0.5 mm: about the thickness of a sheet of paper. On the globe, the commercial airliners are flying no higher than the thickness of a sheet of paper above its surface.*

The atmosphere consists of a mixture of gases. Dry air contains roughly (by volume) 78.08% nitrogen, 20.95% oxygen, 0.93% argon, 0.038% carbon dioxide and small amounts of other gases. It also contains some water vapour, normally around 1%.

There is no definite boundary between the top of the atmosphere and outer space. As you rise from sea level, the air becomes increasingly thin, finally becoming unnoticeable at about 400,000 ft. 50% of the atmosphere's mass is within 18,000 ft of sea level and 75% within about 36,000 ft.

As listed in figure 4.2,[2] various layers are defined in the atmosphere, based on their temperature characteristics.

We spend most of our lives in the troposphere, the lowest layer of the atmosphere, with a top usually between about 23,000 ft above sea level (ASL) at the poles and 56,000 ft ASL at the equator. In the troposphere temperature decreases with height.

The troposphere ends with the tropopause, above which the temperature no longer drops with height. Almost all aircraft fly in the two lowest layers of the atmosphere.

4.2.2 The Standard Atmosphere

Any model of the earth's atmosphere can only be an approximation, but the International Organisation for Standardisation (ISO) has defined, in document ISO 2533, the *International Standard Atmosphere* (ISA). Although there probably has never been, and never will be, a day when the real atmosphere accords with this standard atmosphere, having a standard allows us to say

[2]There are layers above the Mesopause (the Thermosphere, Thermopause, Ionosphere, Exobase and Exosphere) but they are not important for meteorology.

Layer	Base (ft ASL)	Lapse Rate (Cdeg/1000ft)	Base Temp. (°C)	Base Pressure (pascals)	Base Pressure (inches Hg)
7: Mesopause	282,152		-86.2	0.3734	0.000110
6: Mesosphere	235,571	-0.61	-58.5	3.9564	0.00117
5: Mesosphere	168,678	-0.85	-2.5	66.939	0.020
4: Stratopause	155,348	+0.0	-2.5	110.91	0.033
3: Stratosphere	105,518	+0.85	-44.5	868.02	0.255
2: Stratosphere	65,823	+0.3	-56.5	5,474.9	1.617
1: Tropopause	36,152	+0.0	-56.5	22,632	6.683
0: Troposphere	0	-1.98	+15.0	101,325	29.92127

Figure 4.2: The Standard Layers of the Atmosphere

that the temperature today is lower than or the atmospheric pressure is higher than "standard".

The standard atmosphere defines how pressure, temperature, density, and viscosity of the atmosphere vary at different heights on a "standard day". Some of the useful values of that atmosphere are listed in figure 4.2. The following points should be noted:

- Almost all general aviation and commercial flying occurs in the Troposphere and Tropopause.
- The standard temperature at the base of the Troposphere (i.e., sea level) is 15°C.
- The standard pressure at the base of the Troposphere is about 29.9212725″ Hg.
- Within the Troposphere, the temperature drops at approximately 1.98 Cdeg per 1,000 ft.
- Once the Tropopause is reached, the temperature ceases to drop with height and, once into the Stratosphere, it starts to increase with height.

It should again be emphasised that this is the *standard* atmosphere. The *real* atmosphere can be very different: we all know that the temperature at sea level is not always 15°C, the pressure at sea level fluctuates throughout the day and on some days, temperature in the troposphere increases, rather than decreases, with height—see section 4.3.3. Furthermore, the height of the tropopause is much lower over the poles (sometimes reaching almost down to sea level) than it is over the equator. Figure 4.3 illustrates the difference of altitude of the tropopause by comparing the temperatures aloft over Kugluktuk, Nunavut and Miami, USA at the same time on the same winter's day. Clearly the surface temperature is much colder in Kugluktuk but, above about 35,000 ft, the temperature over Kugluktuk is actually warmer than that over Miami—because the tropopause is lower.

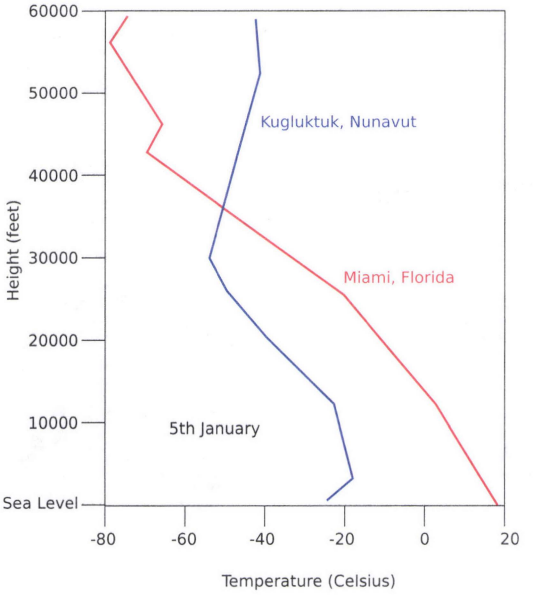

Figure 4.3: Warmer over Kugluktuk or Miami?

4.2.3 Mobility, Expansion & Compression

The atmosphere consists of gases; by their nature, gases move around easily and can be compressed and expanded. The atmosphere is often compared to an ocean, with humans living on the ocean floor. While this is often a useful analogy, it must be remembered that gases are more mobile than liquids and will expand and compress to fill the space available to them. For example, although a container can be half full of water, it is impossible to have a container half full of air. When dealing with small containers of air we can assume that the air will expand uniformly to fill the container. In something as large as the atmosphere, the air is compressed at lower levels by the weight of air on top of it: see figure 10.11 on page 207.

4.3 Temperature

4.3.1 Atmospheric Temperatures

It comes as a surprise to some people that the troposphere tends to get cooler the higher one goes. It could be imagined that if the sun is warming the atmosphere then the higher parts of the atmosphere, being closer to the sun, should be the warmest. In fact, the atmosphere is largely being warmed from below: from the warmth of the earth.

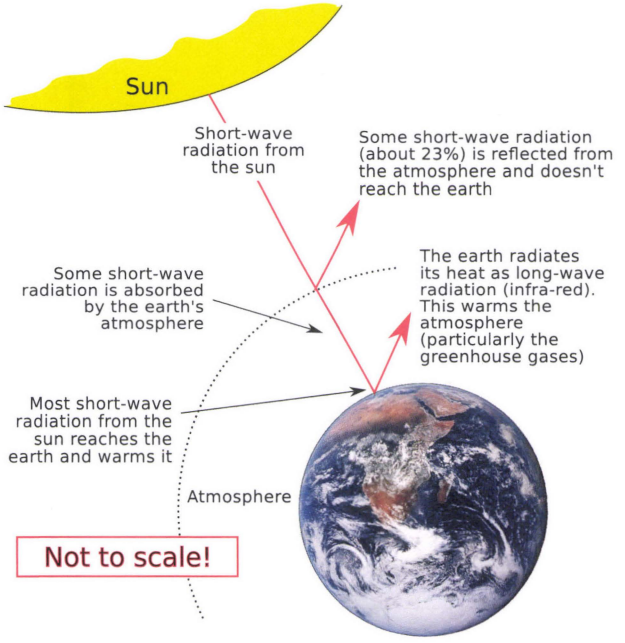

Figure 4.4: Atmospheric Heating

As illustrated in figure 4.4, short-wave radiation from the sun passes through the atmosphere almost without warming it, and reaches the earth. The earth warms up and warms the atmosphere:

- by convection—the warm air in contact with the earth rises through the atmosphere
- by radiation—the earth radiates at longer wavelengths, infrared, that the atmosphere can absorb.

Note that, in accordance with anecdote 12, figure 4.4 is very out of scale—with the earth that size, the depth of the atmosphere should be much less than a millimetre thick and the sun should be in the next town!

The long-wave radiation from the earth is particularly absorbed by the so-called "greenhouse gases": water vapor, carbon dioxide, ozone and methane. There is a greater concentration of these near the earth's surface, so more heat is absorbed closest to the surface and less with increasing height.

The atmosphere gains 11.9% of its heat by absorbing the short-wave radiation from the sun, 14.4% from the latent heat released by condensing water vapour, 4.4% from convection and 69.4% from long-wave radiation from the earth.

Bearing in mind that global warming modifies this claim, the atmosphere is, over the long term, neither warming nor cooling. This means that whatever heat it is gaining, it must also be losing. This occurs with 40% of the atmosphere's heat escaping into space and 60% being passed back to the earth.

4.3.2 Horizontal Differences

The temperature of the lower atmosphere varies horizontally. On the large scale it generally decreases as one moves from the equator, where the sun is more directly overhead, to the poles, where the sun is at a much lower elevation and where its rays must pass through more of the atmosphere before reaching the ground.

On the small scale it varies according to many factors including cloud cover (the sun will heat the ground and thereby the lower atmosphere where there is less cloud cover) and surface conditions (roads, for example, absorb and radiate more heat from the sun than grass).

4.3.3 Temperature & Altitude

As described in section 4.3.1, the temperature within the troposphere generally drops with height. The rate at which it drops varies both by time and place but the standard rate is defined to be 1.98 Cdeg per 1,000 ft.

However, it is not always the case that temperature drops with height: sometimes warmer air is found aloft—this is known as an **inversion**. There are several causes of inversions:

- when a warmer, less dense air mass moves over a cooler, denser one. This happens ahead of a warm front (see section 4.7.1).
- on cold nights with little cloud cover when the heat from the surface of the earth radiates out into space. The ground cools and this cools the air close to it.
- when air in a high pressure region gradually sinks over a wide area. As it sinks it is warmed by adiabatic compression (see section 4.1.3), producing a layer of warm air aloft. This process is known as **subsidence inversion**.

Generally inversions are quite shallow, the temperature starting to drop above a few thousand feet but, in the arctic winter, they can reach to 10,000 ft.

As described in section 4.10.1 on page 78, an inversion produces very stable air with little or no convective activity. This itself means that pollutants in the air (e.g., dust, smoke particles) are not carried upwards and dispersed and the air near ground level therefore becomes dirty, creating smog. This is a problem in many cities where pollutants are generated (e.g., Mumbai, Los Angeles, Mexico City) because the poor quality air can cause respiratory problems. The "Great Smog" of 1952 in London, England was caused by a prolonged inversion.

4.3.4 Isothermal Layers

The term **isothermal** simply means "at the same temperature". As explained above, temperature generally changes with altitude in the troposphere. The tropopause (above the troposphere), stratopause (above the stratosphere) and the mesopause (above the mesosphere)—see figure 4.2)—are all isothermal layers, where the temperature does not change with height.

An inversion near the surface of the earth can also sometimes be so weak that its temperature hardly changes with height—producing an isothermal layer.

4.4 Air Masses

The troposphere consists of a number of *air masses*, each being a large body of air with approximately the same temperature and humidity. You might expect that the air masses would merge at their borders and this does occur to a small extent but there is little actual mixing of the air across the boundaries.

4.4.1 Formation/Classification

An air mass forms when a portion of the atmosphere remains in contact with a large, uniform land or sea surface for a long time. During the year, some of the air masses grow and others shrink, and the dynamic behaviour along their borders causes much of the earth's weather.

Figure 4.5 shows the primary air masses that affect North America. These air masses are classified by their temperature:

- Arctic—very cold
- Polar—cold
- Tropical—warm
- Equatorial—very warm

and by their moisture content:

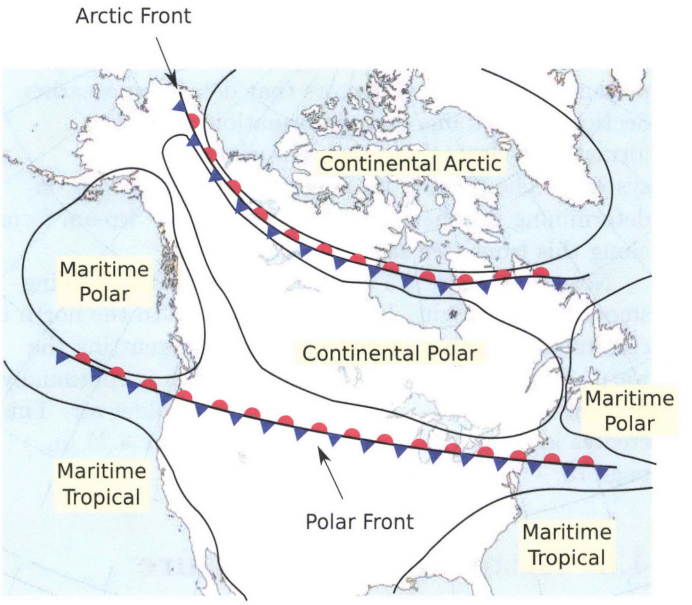

Figure 4.5: North American Air Masses

- Continental—dry (generally forming over large areas of land or ice)
- Maritime—moist (generally forming over large areas of water)

In general, air masses over land (or frozen sea) tend to be dry and are termed **continental**.

In the summer a continental tropical air mass (not shown in figure 4.5) can form in the western USA: a dry, hot air mass.

4.4.2 Seasonal Effects

Air masses are not static: they move around and can acquire different attributes from the area over which they are moving. For example, in winter an arctic air mass (very cold and dry air) can move over a section of unfrozen ocean, picking up some warmth and moisture and becoming a maritime polar air mass. The arctic air mass could have moved south, picking up warmth from the ground, but due to lack of moisture remained very dry: becoming a continental polar air mass.

As you would expect, the relative size of the air masses changes dramatically between summer and winter. During the summer the cold, continental air retreats towards the arctic and the polar front moves northwards: in the winter it lies around 30° north and during the summer at about 60° north.

4.4.3 Factors that Determine Weather

The boundary between two air masses can be quite sharply defined and, if so, is called a **front**. As the two

air masses move relative to each other, shearing motions occur along the front, creating areas of low and high pressure—the primary factors that determine weather. Section 4.7 contains more information about the formation of fronts and their associated weather systems. The polar front is particularly important in determining weather because the Polar Jet Stream forms along this front (see section 4.6.13).

Note that figure 4.5 shows the polar front as being smooth and straight. In fact, the cold air to the north is continually pushing southwards and undercutting the warmer air and the warm air in the south is continually pushing northwards and riding over the colder air. This creates kinks in the front as shown in figure 4.21 on page 73.

4.5 Atmospheric Pressure

As background to this section see page 51 for a description of the different pressure units used in meteorology and refer to page 58 for the two ways pressure is represented on a chart.

4.5.1 Pressure Measurements

Air has weight[3] and each of us, sitting at the surface of the earth, has a weight of air pressing down on us. We are not crushed because the same force is also acting upwards upon us: we are immersed in the ocean of air. Atmospheric pressure is a measure of the weight of the atmosphere over a particular area at a particular place.

Anecdote 13 *When flying on a commercial airliner, I like to seal an empty plastic water bottle while at altitude. As the aircraft descends through the altitude to which it has been pressurised (typically about 8,000 ft), the bottle collapses as the outside air pressure increases—a visible indication of the pressure of the atmosphere.*

Of course, the opposite occurs when you put a large bag of chips in the back of your unpressurised aircraft and then climb. The outside air pressure drops, the bag swells and eventually bursts with a bang sufficient to frighten passengers.

Atmospheric pressure can be measured in a number of ways. Many smaller aerodromes use one or more calibrated aircraft altimeters. Each altimeter is adjusted to read the altitude of the aerodrome, and the pressure is read from the pressure window. This is using an altimeter in reverse—in an aircraft the pilot sets the pressure and reads the altitude; to measure pressure, the operator sets the altitude and reads the pressure.

At Flight Service Stations more precise measurements are made using mercury barometers: essentially the apparatus illustrated in figure 3.1 on page 51.

4.5.2 Station & Sea Level Pressures

As illustrated in figure 4.6, the higher a measuring station is above sea level, the smaller the column of air above it and therefore the lower its atmospheric pressure. Thus, two measuring stations close together but at different heights above sea level would measure different atmospheric pressures. This is resolved by each station reporting:

1. its actual measurement: the **station pressure.** This is known by the term QFE[4] in Europe. Setting your altimeter to this pressure causes it to read an altitude of 0 ft when on the ground.

2. the pressure corrected to what it would be at sea level: the **sea level pressure**. Imagine a large shaft dug down to sea level. The pressure at the bottom of the hole is the sea level pressure. To avoid having to dig a deep hole, given the height of the station above sea level and the temperature, it is possible to calculate what the pressure at sea level would be. This is known as QNH in Europe; setting your altimeter to this pressure causes it to read the height of the aerodrome above sea level when you are on the ground.

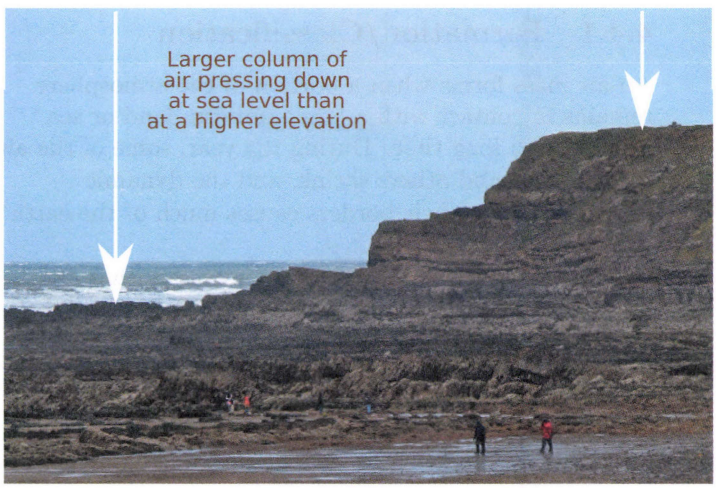

Figure 4.6: Measuring the Pressure at Different Altitudes

[3]The total mass of the atmosphere varies throughout the year as water vapour increases and decreases but is approximately 5,148,000,000,000,000,000 kg (about 5,675,000,000,000 tons).

[4]The so-called Q codes don't really expand as acronyms. They arose as Morse Code signals for querying pressures. QFE can be thought of as standing for Query Field Elevation (i.e., altitude).

Figure 10.11 on page 207 illustrates how pressure drops with altitude (largely because at higher altitudes there is a lesser weight of air above).

The density of the atmosphere (kg per cubic metre) also decreases with height, dropping by 50% for about every 18,000 ft ASL.

Exercise 19 *If you have a well at your cottage which is 35 ft deep, why can't you use a simple suction pump at the well-head to suck water up?*

Possible answers to the questions in this chapter are given starting on page 91.

4.5.3 Pressure Systems

The atmospheric pressure at the surface of the earth differs from place to place and from time to time—areas of lower pressure (known as **depressions** or **cyclones**) and areas of higher pressure (known as **anticyclones**) form, move, interact and finally dissipate.

To create an area of low or high pressure, a large amount of the atmosphere has to be moved and this requires energy—provided through local heating.

A depression starts when air rises. This could be caused:

- over a relatively small area (say 80 km across) by local daytime heating, causing warmed air to rise and form a "dome" in the pressure layers (the contour lines explained on page 58). This causes the air above the dome to flow away from the warmer area—known as **divergence**—and a low pressure to form. Low pressure areas of this type are typically short-lived, collapsing at sunset when the heat source disappears. Sometimes, however, and particularly in the tropics, they live long enough for the next stage of formation to occur.

- over a larger area when the high altitude winds (e.g., a jet stream) are strong and *divergent*, i.e., when the streams of air are not moving parallel to each other but are moving apart. This divergence "sucks" lower air upwards in much the same way as the local heating described above but over much larger areas.

Whatever causes the air to start rising, the rising air expands and cools and, if it is moist, water vapour condenses out of it. This releases latent heat which provides another source of energy for the forming low pressure.

The lowering of pressure at the surface causes the cooler surrounding air to move in. If the low pressure persists long enough, the inflowing air is affected by the rotation of the earth (the *Coriolis Force* discussed in section 4.6.4). The incoming air starts to rotate, and this causes the low pressure to deepen.

4.5.4 Effects of Temperature

Cold air is denser than warm air but, more importantly, pressure drops more rapidly with altitude in cooler air. At 30°C, for example, the pressure drops at 1.00″ Hg per 1,000 ft. At −30°C it drops at 1.19″ Hg per 1,000 ft: 19% faster.[5]

The impact of this change can be dramatic: altimeters are calibrated to read correctly when the outside air temperature at sea level is 15°C and when the pressure drops with height in the manner expected at that temperature. When the pressure drops faster (i.e., when it is cold), the altimeter will indicate an altitude higher than is actually correct—very dangerous when making an instrument approach. NAV CANADA publishes a table in the general pages of the *Canada Air Pilot* giving correction values to be added to various altitudes during IFR approaches in cold weather. For example, at 2,000 ft above the station measuring the pressure, if the temperature is −30°C, 380 ft must be added to all heights on approach plates.

4.5.5 Pressure Differences

As described in section 4.5.3, the atmospheric pressure differs with location and time. Since atmospheric pressure is one indicator of the weather likely to be encountered at a location, it is important that meteorologists be able to record their reading and predictions of atmospheric pressure in a graphical form.

Figure 4.7 is a chart where the sea level pressure has been measured at a number of points and plotted, with all the points having the same sea-level pressure being

[5] It is not required for the Transport Canada examination but you may be interested in the formula from which these values have been computed. Here, the standard pressure formula (equation 4.1) has been differentiated. The result has been converted from pascals per metre to inches of mercury per 1,000 ft.

$$P = P_b \times e^{\frac{-g \times M \times h}{R^* \times T}} \tag{4.1}$$

where:

- P_b is the standard pressure (101325 pascals)
- g is the gravitational constant (9.80665 metres per second per second)
- M is the molar mass of Earth's air (0.0289644 kg per mol)
- h is the height above sea level (metres)
- R^* is the universal gas constant: (8.31432 Nm per mol per kelvin)
- T is the temperature (kelvins)

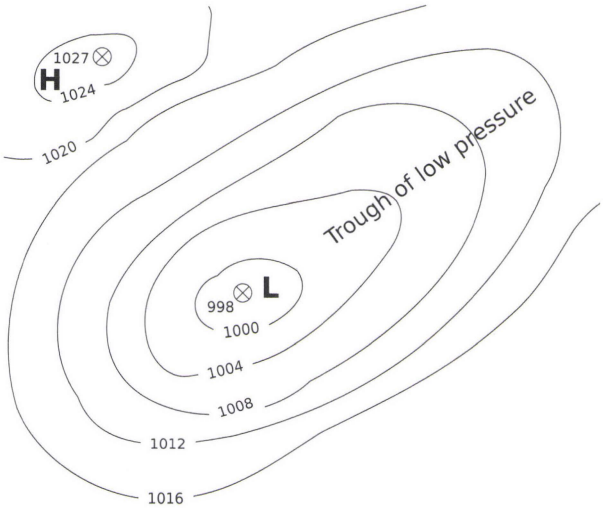

Figure 4.7: Sea Level Pressures: 1 of 2

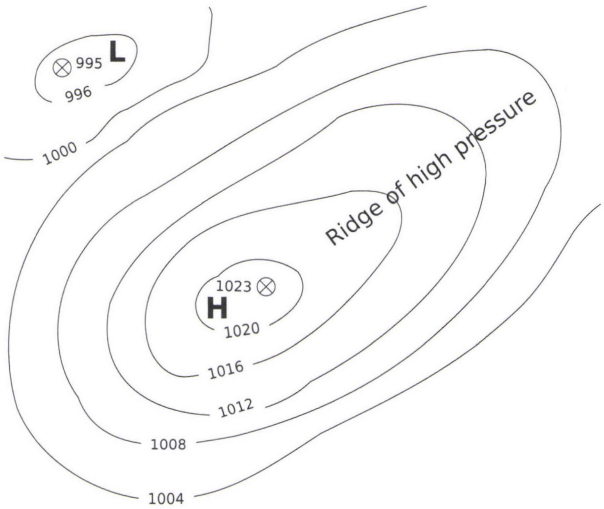

Figure 4.8: Sea Level Pressures: 2 of 2

joined together with lines known as **isobars.** The innermost ring joins together all the places where the sea level pressure is 1,000 hectopascals. The next ring, 1,004 hectopascals, and so on at 4 hectopascal intervals.

You can see that if these were contour lines on a normal map then the area marked **L** would be at the bottom of a dip: all paths into **L** would be down hill. Similarly the area marked **H** represents the top of a hill and the **trough** would be a valley.

Low pressure areas may be very small (as in the centre of a tornado) or very large (covering a large part of the North American continent). The deepest low ever recorded was 870 hectopascals in the centre of Typhoon Tip (16°44′ N, 137°46′ E) in 1979. Outside tropical storms, 916 hectopascals was recorded on 10th to 11th January 1993 in the North Atlantic.

Figure 4.8 has the same lines as figure 4.7 but represents a very different situation. The innermost ring now represents an area of high pressure and a **ridge** of high pressure leads away from it. There is no record of the highest pressure ever measured but pressures of 1040 hectopascals are not uncommon. Areas of high pressure are sometimes called **anticyclones**.

In general, wind will flow from an area of high pressure to an area of low pressure, although as described in section 4.6.4, not directly. Except when you are close to the equator, isobars allow you to estimate both the direction and strength of upper winds—winds well above the ground tend to follow the isobars (or contours) and the closer the isobars (or contours) are, the stronger the wind. Near the equator isobars do not give an accurate indication of winds and are often replaced on weather charts by streamlines indicating wind direction.

4.6 Wind

Wind is simply a movement of air, either horizontally or vertically. Except in thunderstorms, vertical movements of air are generally much slower than horizontal movements and, although vertical movements are important (for example in creating low pressure areas), this section deals almost exclusively with horizontal movement of the air.

One very important factor to remember when winds are discussed is that the direction given for a wind is the direction *from* which it is blowing. Thus, a westerly wind is one blowing *from* the west *to* the east.

Exam Hint 4 *It is also important to notice whether the wind direction is given in degrees true (relative to the north pole) or degrees magnetic (relative to the magnetic north pole). Wind directions in weather reports and forecasts are true; wind directions provided by ATC on approach or by an ATIS are magnetic.*

Winds of different speeds have, over history, been given different names: breezes, gales, storms, hurricanes, etc. In 1805 Sir Francis Beaufort devised a wind naming system to be used by sailors: see figure 4.9.

Winds also affect different geographical areas: section 4.6.9 describes land/sea breezes which are local to one small area and last at most a few hours; the tropical *trade winds* affect almost the whole of the earth and blow permanently. Large-scale winds are driven primarily by the differential heating between the equator and the poles and the earth's rotation (see section 4.6.4). Together these cause the circular motion of air around areas of high and low atmospheric pressure.

Name	Speed (knots)
Calm	less than 1
Light Air	$1 \rightarrow 2$
Light Breeze	$3 \rightarrow 6$
Gentle Breeze	$7 \rightarrow 10$
Moderate Breeze	$11 \rightarrow 15$
Fresh Breeze	$16 \rightarrow 20$
Strong Breeze	$21 \rightarrow 26$
High Wind, Moderate Gale	$27 \rightarrow 33$
Fresh Gale	$34 \rightarrow 40$
Strong Gale	$41 \rightarrow 47$
Whole Gale	$48 \rightarrow 55$
Violent Storm	$56 \rightarrow 63$
Hurricane	64 or more

Figure 4.9: The Beaufort Wind Scale

4.6.1 Wind Speed & Direction

This section describes how the likely wind speed and direction can be estimated from a surface analysis or upper-air chart. There are many different factors that influence wind speed and direction including:

- the difference in pressure between the high pressure area *from* which the wind is blowing and the low pressure area *to* which it is blowing. This is known as the **pressure gradient**—see section 4.6.2.
- the rotation of the earth and the latitude of the observing point—see section 4.6.4.
- the shape of the isobars or contours around the high and low pressure areas—see section 4.6.4.
- the rate at which the pressure is changing in the low and high pressure areas—see section 4.6.4.
- the height above the ground at which the wind is being observed—see section 4.6.5.
- the time of day—see section 4.6.8.
- the location of the jet streams—see section 4.6.13.
- the relationship of nearby bodies of water and land—see section 4.6.9.

As you can imagine, when these factors combine, estimating wind speeds and directions is not trivial.

Exam Hint 5 *To find the general direction of the wind from a surface analysis chart remember that, if you stand with your back to the wind in the northern hemisphere then the low pressure is on your left. This is known as Buys Ballot's law after the Dutch meteorologist C. H. D. Buys Ballot.*

The two words **veer** and **back** are used to describe changes in the direction of the wind. When viewed from above, a clockwise movement in the direction from which the wind is coming (e.g., from North to East) is known as *veering*. A counter-clockwise movement (e.g., from North to West) is known as *backing*.

4.6.2 Pressure Gradient

As described on page 58, there are two ways to represent and visualise the pressure differences in the atmosphere:

1. by drawing isobars that join all points having the same sea-level pressure. Thus, as shown in figure 4.7 on page 64, a line might be drawn through all of the points having a sea level pressure of 1008 hectopascals.
2. by drawing contours that join all points having the same altitude for a given pressure. Thus, as shown in figure 5.17 on page 110, a line might be drawn through all points where the 500 hectopascal pressure is to be found at 5,700 metres (18,701 ft) above sea level.

Either type of chart can be used to predict the strength of winds and the direction in which they will blow—some people find one type of chart easier to use, some people the other.

In general, this section refers to isobars and addresses wind as being caused by differences in pressure. It would be very simple to modify this description to refer to contours and show how wind is caused by air literally moving downhill.

If two places have different atmospheric pressures then there is said to be a **pressure gradient** between them. The pressure gradient is a measure of how much the pressure changes over a particular distance. Figure 4.7 on page 64, for example, shows an area of low pressure (marked L) and an area of high pressure (marked H). The difference in pressure between these two points is $1027 - 998 = 29$ hectopascals. Assuming the L and H are 100 nm apart, the pressure gradient between them would be $\frac{29}{100} = 0.29$ hectopascals per nautical mile.

Exercise 20 *Assume that the H and L in figure 4.8 on page 64 are 150 nm apart. What is the average pressure gradient between the H and L?*

If figures such as 4.7 and 4.8 are thought of as showing contour lines on a map, then the pressure gradient is a measure of how "steep" the "hill" is. As with contour lines on a map, the closeness of the isobars

is an indication of the steepness of the pressure gradient—if the contour lines are close together then the pressure gradient is steep and the wind strong.

Generally wind moves from an area of high pressure to an area of low pressure and the strength of the wind depends on the steepness of the pressure gradient. If the earth were not rotating, then the wind would blow directly from the high pressure to the low pressure, but the earth's rotation modifies this—see section 4.6.4.

On a much smaller scale, we could think of the concept of air flowing from an area of higher to an area of lower pressure when we breathe. Our muscles expand or decrease lung volume which decreases or increases the air pressure in the lungs. These pressure changes cause air to enter or leave the lungs.

4.6.3 Geostrophic Winds

Geostrophic winds are those winds at such an altitude that they are not affected by friction with the surface of the earth—typically the winds above 2,000 ft AGL. The strength of the geostrophic winds can be estimated from the isobars on a surface analysis chart or from the altitude contours on an upper-air chart: the closer together the isobars or contours, the stronger the wind.

To estimate the geostrophic wind speeds, draw a line 300 nautical miles (5 degrees of latitude) long, at right angles to the isobars or contours. Note the difference in altitude (metres) or pressure (hectopascals) at the ends of the line and use figure 4.10 to find the factor to multiply by the difference to estimate the wind strength in knots.

Latitude (N)	Multiplication Factors	
	Isobars (hectopascals)	Contours (metres)
70°	2.1	0.25
60°	2.3	0.27
55°	2.4	0.29
50°	2.6	0.31
45°	2.8	0.33
40°	3.1	0.37

Figure 4.10: Wind Speed Estimation

Exercise 21 *Consider the portion of a Graphical Area Forecast (GFA) in figure 4.11. CYLL (Lloydminster, AB) and CYQD (The Pas, MB) are 322 nautical miles apart. Estimate the pressure gradient and the strength of the geostrophic winds between these two aerodromes.*

In practice, it would probably be more practical to obtain the forecast for the winds aloft from the FDs and FBs; see section 5.4.3 on page 104.

4.6.4 Deflection Caused by the Earth's Rotation

In 1835, Gaspard-Gustave Coriolis published a paper about the physics of rotating bodies (particularly water wheels). He realised that for some calculations it was easier to assume that the rotating body was stationary and that the rest of the universe was rotating.[6] When he did this he found that two imaginary forces appeared in his calculations: *centrifugal force* and what he called *compound centrifugal force*. Neither of these forces exist in what mathematicians call an inertial reference frame—instead they are fictions created in the mathematics by assuming that the rotating body is stationary.

In the 20th century the compound centrifugal force was renamed the **Coriolis Force** and it was found useful for meteorology. The earth is a rotating body but, for weather forecasting purposes, it is often simpler to assume that it is stationary, and Coriolis and centrifugal forces then appear in the mathematics. When viewed by an observer who is treating the earth as stationary, the Coriolis Force appears to make all freely-moving bodies in the northern hemisphere deflect to the right (and in the southern hemisphere, to the left). This deflection is greatest at the poles and does not exist at the equator.

Wind is a freely-moving body and is therefore subject to the Coriolis Force. Figure 4.12 illustrates the two primary forces acting on a body of air:

1. The pressure gradient causes a force that, in the absence of the earth's rotation, would cause the wind to move directly from the high pressure to the low pressure.

2. Initially the wind *does* start to move directly from the high pressure to the low pressure but, once it starts moving, it is subject to the Coriolis Force which makes it deflect to the right.

Eventually these two forces balance and the wind flows more-or-less parallel with the isobars (or, on upper-air charts, parallel with the contour lines).

In practice, winds are rarely precisely geostrophic. Figure 4.12 "cheats" by having isobars that are straight and parallel. Generally this does not occur—isobars are curved and are not uniformly spaced. If air tries to flow

[6] If you were calculating the trajectory for sending a rocket to the moon, it might be easier to assume that the sun rotates around the earth; if you were sending a rocket to the sun, it might be easier to assume that the earth rotates around the sun—the aim is just to simplify the mathematics.

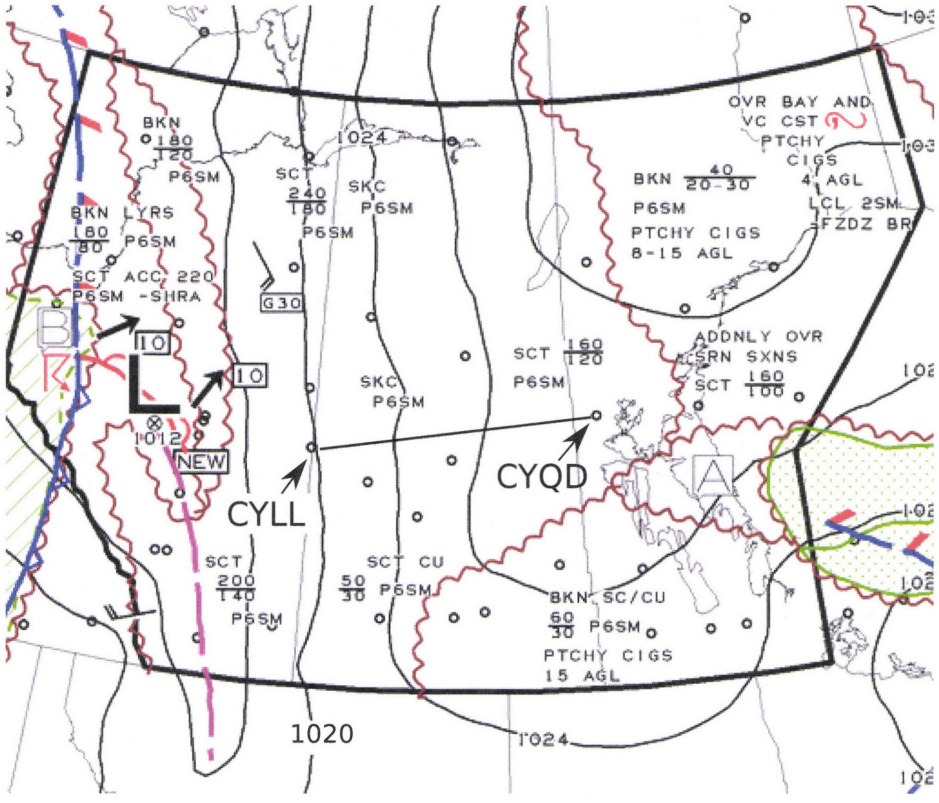

Figure 4.11: GFA (portion) for Exercise 21

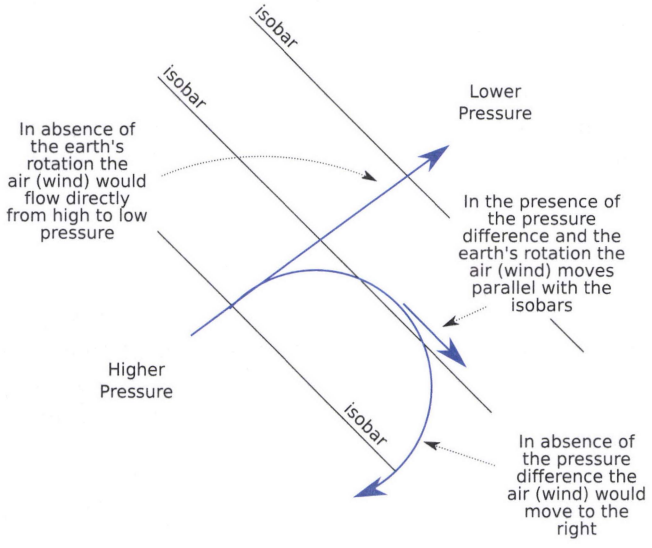

Figure 4.12: The Forces Acting on the Geostrophic Wind

parallel to the isobars when the isobars are curved, a second "force" (caused by considering the earth to the stationary) appears—a *centrifugal force* tending to act outwards on the moving air. Figure 4.13 shows how:

- around an area of high pressure the centrifugal force and the force caused by the pressure gradient tend to reinforce each other. This causes a stronger wind which does not follow the isobars.
- around an area of low pressure the centrifugal force and the pressure gradient force tend to cancel each other out. This causes a less strong wind that does follow the isobars.

Another disturbance that causes the wind to flow across, rather than parallel to, the isobars (or contours) is a rapid change in pressure. If, for example, a low pressure area is deepening rapidly then the wind will tend to flow much more directly towards it. This is known as the **isallobaric wind** and it follows the isallobaric lines on a chart—lines joining all points which have the same rate of change of pressure. This chart is not available from NAV CANADA, but is available from sources in the USA.

4.6.5 Low Level Winds

Close to the surface of the earth the wind is slowed down by friction with the ground. This slowing lessens the effect of the Coriolis Force and the wind therefore does not turn to the right as much. It therefore appears to turn to the left, to *back*. The amount of friction generated, and therefore the reduction in speed and

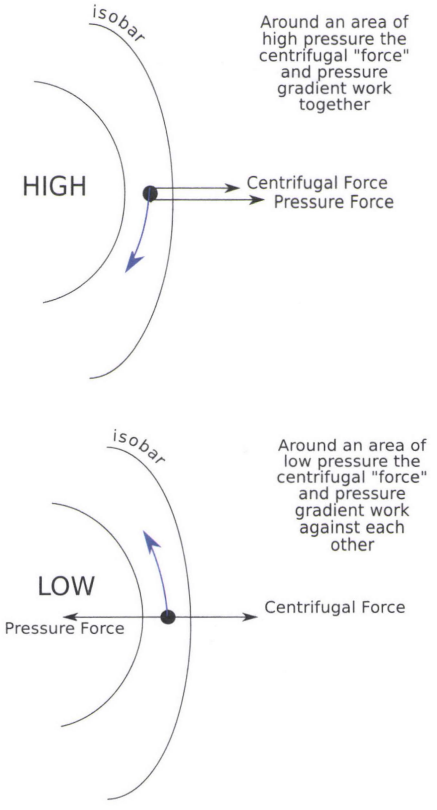

Figure 4.13: Centrifugal and Pressure Gradient Forces

degree of backing, depends on the surface. It is least over bodies of water and flat plains and most over mountainous areas. The friction also depends on the stability of the air—as figure 4.32 on page 81 illustrates, the friction is greater in stable air which tends to "hug" the ground.

Because of this, when descending for landing, an aircraft meets winds that are backing and decreasing in intensity. Similarly, it meets veering winds increasing in intensity as it climbs after takeoff. This effect is normally only noticeable below about 2,000 ft AGL where the friction is significant.

Exam Hint 6 *One can always remember whether the wind backs or veers as one descends by remembering to expect the wind to* **back** *as you come* **back** *to the airport to land.*

4.6.6 Centrifugal Force

As explained in section 9.5.10 on page 188 there is no such thing as centrifugal force—it simply does not exist. However, together with the Coriolis "force" it is a useful fiction that arises because of the assumption made by meteorologists that the earth is stationary rather than rotating. See section 4.6.4 for more details.

4.6.7 Squalls/Gusts

Winds which sharply increase in speed are termed **squalls** or **gusts.** The official definitions of the terms vary from country to country but in Canada:

- a **squall** is reported when the wind increases by at least 15 knots over the average speed for a duration of at least 2 minutes and the wind reaches a speed of at least 20 knots.
- a **gust** is reported when the highest peak speed is at least 5 knots higher than the average wind and the highest peak speed is at least 15 knots.

For information about the *gust front* associated with a *squall line* see section 4.15.5 on page 90.

4.6.8 Diurnal Effects

The term **diurnal** means "occurring in a 24-hour period".

In most locations it is windier at ground level during the daytime than at night. This is largely due to increased temperature differences and the resulting decrease in stability of the atmosphere. The wind also tends to be more turbulent and to change direction more frequently during the day than at night.

The diurnal effect also depends on altitude: at ground level, the winds back and decrease during the night; above the frictional layer they tend to veer and increase at night.

4.6.9 Land/Sea Breezes

The phenomenon of land/sea breezes[7] was noticed thousands of years ago and the first attempt to explain its origins was probably that in *Problemata Physica* attributed to Aristotle and written in the 2nd Century BCE. The explanation is wrong, but its existence indicates that the phenomenon had been observed.

Soil has a lower specific heat than water. This means that it warms up more quickly than water when the sun shines on it, and cools down more quickly when the sun sets.

Consider an airport such as Kingston, Ontario (CYGK). Kingston has a north/south runway 01/19 and the threshold of 01 is only a few metres away from Lake Ontario. On a hot summer's day the land around Kingston airport will heat up more quickly than the lake. The air over the land will therefore warm up and

[7] Also called off-shore/on-shore breezes.

start to rise, reducing the local pressure by about 0.2% and sucking in the cooler, higher-pressure air from above the lake. This will cause an on-shore breeze from the water to the land—it is likely that runway 19 would be in use at such a time. This miniature cold front also causes a drop in temperature and a rise in relative humidity over the land.

After sunset, the land will cool rapidly while the lake will hold its warmth. After a time the lake will be warmer than the land and the opposite effect will occur: warmer air over the lake will rise, sucking in air from over the land, causing an off-shore breeze. Runway 01 is more likely to be in use at such a time. This off-shore breeze is usually less strong than the equivalent on-shore breeze.

Land/sea breezes only occur when the "normal" wind is less than about 8 knots. Contrary winds stronger than this will block the formation of land/sea breezes.

4.6.10 Katabatic/Anabatic Effects

The word *Katabatic* comes from the Greek word "katabatikos" meaning "going downhill". The word *Anabatic*, in contrast, comes from the Greek word "anabatos" meaning "going uphill".

Consider a parcel of air at the top of a hill, mountain or (frequently) glacier. As night falls, heat is radiated from the high ground and the parcel of air cools. This increases its density and it starts to move downhill under gravity—a sort of air avalanche. Of course, as it moves downhill, it is compressed by the increasing pressure of the surrounding air and therefore warms. The *Mistral* in the Mediterranean, the *Bora* (or Bura) in the Adriatic, the *Santa Ana* in southern California and the *Oroshi* in Japan are all katabatic winds but not all downslope winds are katabatic; the *Föhn*, *Chinook* and *Bergwind* are downslope winds which are not caused by radiation cooling.

Various studies have measured katabatic winds and they have been found to be the strongest between 20m and 30m above the surface of the hill. One researcher, H. Scaëtta, actually reports his tent being blown away by katabatic winds while he was taking measurements around Lake Kiwu. One useful effect of katabatic winds is that they will often dissipate valley fog—see section 4.12.1—as they blow down the slope into the valley.

Anabatic winds normally occur during the daytime in calm sunny weather. A hill or mountain top is warmed by the Sun's radiation while the valley below is still in shade. This heats the air at the top of the hill and, because it is now warmer than the air around it, it rises through convection creating a lower pressure region "sucking" the air lower down the slope upwards, causing a wind. Often the rising air reaches a height where it cools to a temperature below its dew point and forms cumulus clouds. This is why one often sees a line of clouds over a ridge and these winds are particularly useful for glider pilots who can use them in "ridge soaring".

4.6.11 Topographical Effects

The term *topographical effect* means the effect that the topography of the ground (buildings, hills, valleys, forests, etc.) has on the local winds. There are actually two types of topographical effects:

1. Active Topographical Effects. These are the topographical features that actually cause winds. Examples include the katabatic and anabatic winds described in section 4.6.10—in this case the winds arise because of the hills.

2. Passive Topographical Effects. These are the effects caused by the local topography on winds generated elsewhere which pass over the area. The major passive topographical effect on wind is "orographic channelling": the effect where the wind direction is changed as the wind is channelled between mountains, speeding up as it does so. See section 11.3.5 on page 237 and, in particular anecdote 37, for more details of this effect.

Of course, it is not only that the topographical features affect the wind direction and speed—architects designing buildings must design for the effects of the wind on their buildings, part of the topography of an area. The ESDU[8] publishes tables of the so-called *K-value* for a variety of surfaces (ploughed, grass, trees, etc.). The K-value is a measure for the effect that the surface has on the wind at different heights above the ground and is used to calculate the stresses on buildings and other structures.

4.6.12 Wind Shear

Wind shear is a significant difference in the speed and/or direction of the wind over a relatively short distance, either vertically or horizontally.

If, for example, the wind at the surface is reported to be from 120°T at 10 knots and at 3,000 ft it is from 180°T at 25 knots then somewhere in between there must be a vertical wind shear: a significant change in direction and speed of the wind as we climb up.

An example of horizontal wind shear often occurs close to a thunder cell. Air may be rising rapidly into the cell at one point and, five miles further on be

[8] Formally the *Engineering Standards Data Unit* but now just the acronym.

descending rapidly—if we fly horizontally, maintaining altitude, we experience intense wind shear.

Being able to visualise the wind shear is very important when forecasting the strength of thunderstorms (see section 4.15 on page 89) and **Hodographs** are used to visualise vertical wind shear: see the examples in figure 4.15. The first thing to notice in that figure is that the direction at the top is labelled "south", that at the bottom "north", that on the left "east" and that on the right "west". This makes it simpler to plot winds (really!) because wind directions are always given as the bearing *from* which the wind is coming. So, to plot a wind from 190° on the hodograph, one simply draws an arrow from the centre to the point just clockwise of the 12 o'clock position—the point at 190°.

Example 1 in the upper part of figure 4.15 illustrates the wind shear associated with the upper winds listed in the "example 1" column of figure 4.14. Looking at the figure, it is immediately clear that, although the speed of the wind is increasing significantly with altitude, its direction is almost constant, blowing from a generally southerly direction. Of course, this could be deduced by close examination of the numbers in figure 4.14 but it is much easier to see from the hodograph.

Example 2 in the lower part of figure 4.15 also shows shear occurring in the strength of the wind (from 24 knots at 500 ft to 95 knots at 30,000 ft) but also illustrates shear in the direction of the wind (veering from 110° to 270°).

Examples 1 and 2 are used again in section 4.15 where the likely intensity of the thunderstorms associated with each is discussed.

Pressure Level	Approx Alt	Wind Conditions	
		Example 1	Example 2
950mb	500 ft	130° at 19 kts	110° at 24 kts
850mb	5,000 ft	140° at 35 kts	180° at 43 kts
700mb	10,000 ft	160° at 45 kts	220° at 52 kts
500mb	18,000 ft	180° at 70 kts	250° at 77 kts
300mb	30,000 ft	200° at 85 kts	270° at 95 kts

Figure 4.14: Example Wind Shears (see figure 4.15)

4.6.13 Jet Stream

A jet stream is a narrow band of strong wind usually found between 30,000 and 40,000 ft ASL but sometimes much lower. A jet stream is typically less than 200 miles wide and a few thousand feet high, but can extend for thousands of miles (sometimes with short gaps). The air in the core of a jet stream normally moves at around 100 knots but speeds of 215 knots have been measured.

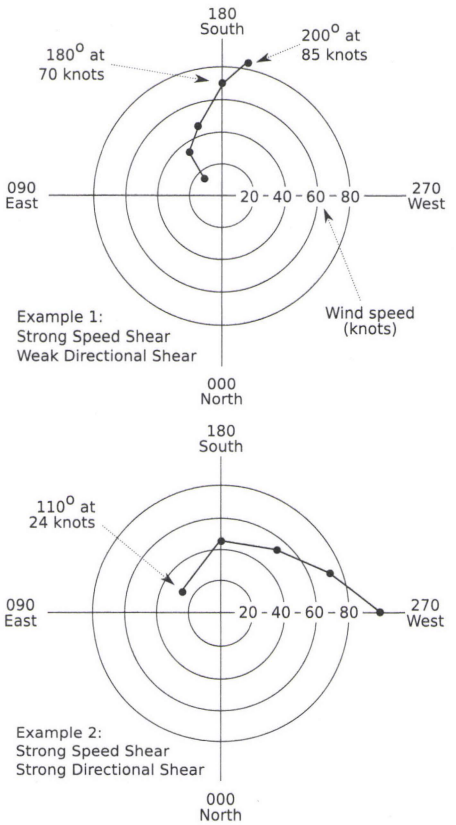

Figure 4.15: Two Hodographs Illustrating Wind Shear

Jet streams were first detected in the 1920s by the Japanese meteorologist Wasaburo Ooishi when he tracked balloons near Mount Fuji.

A jet stream forms at a sharp boundary between air masses with very different temperatures: the border where the height of the tropopause changes. Each hemisphere has two primary jet streams: one in the sub-tropical region and one closer to the poles. The jet stream that normally affects Canada is the polar jet stream that forms along the polar front—see section 4.4 and figure 4.5. Figure 4.16 illustrates a representative path for the polar jet stream—it tends to move northwards in the summer and southwards in the winter.[9] A jet stream tends to meander (meanders are known as **Rossby waves**) as the coriolis force affects its southern excursions. Jet streams can coalesce and split: the polar jet stream (see figure 4.16), for example, often crosses the Atlantic and then splits into two with one part heading south to Spain and the other heading north to Scandinavia.

Figure 4.17 shows a cross-section of the line A—B in figure 4.16. The atmosphere is warmer at B than at

[9]There is also some evidence that the average polar jet stream is moving north year by year: between 1979 and 2001 it moved northward at 2.01 kilometres per year.

Figure 4.16: Representative Polar Jet Stream

A and the altitude at which the pressure has dropped to 300 hectopascal level is higher. Moving from B to A the height of the 300 hectopascal level drops. The jet stream forms around the area when the pressure gradient is steepest.

Knowledge of the current location of a jet stream is important not only to allow airliners to be routed in such a way as to reduce travelling times, but also to predict the formation of areas of low pressure and storms in the lower atmosphere.

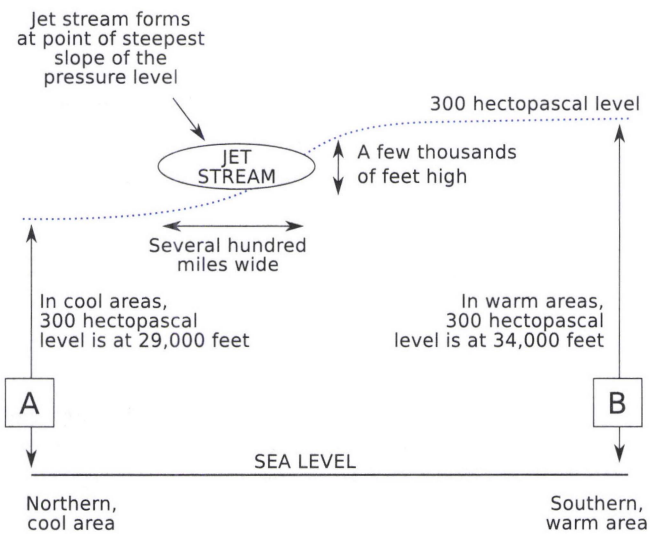

Figure 4.17: Jet Stream Cross-section (A-B in figure 4.16)

The term "low-level jet" is used (see section 11.3.10 on page 239) to refer to a tube of fast-moving air close to the surface of the earth. This is not a "jet stream".

4.7 Frontal Weather

A front is a boundary between two air masses of different temperatures. The term "front" was coined just after the First World War by a group of meteorologists in Norway led by Vilhelm Bjerknes. The way in which the two air masses "struggle" for supremacy and force each other backwards and forwards reminded the meteorologists of the fronts between armies in the battlefield.

Figure 4.21, for example, illustrates the polar front that separates the colder polar air masses to the north from the warmer tropical air masses to the south.

4.7.1 Types of Front

Fronts are named after the air mass that is advancing. If a cooler air mass is forcing a warmer air mass to retreat, then the border between the two air masses is known as a **cold front**. If a warmer air mass is encroaching on a cooler one, then the boundary is known as a **warm front**. Sometimes the encroaching air mass is stopped and a stalemate occurs, with the air masses moving parallel with one another rather than moving forward, creating small oscillations—this is known as a **stationary front.** A stationary front may remain in one place for days, but eventually the emergence of a high or low pressure area close to the front will start one of the air masses moving again.

A front is drawn on a surface analysis chart at the position where the boundary between the air masses touches the ground. In the case of a warm front, this can be hundreds of kilometers behind the leading edge of the warm air mass.

Cold Front

A cold front occurs when a cooler (not necessarily cold!) air mass moves and undercuts a warmer (not necessarily warm!) air mass—see figure 4.18. As the warmer air is undercut it is forced to rise. If it is moist and unstable,[10] it may continue to rise and form cumulus-type clouds. A rapidly-moving cold front in summer can produce a line of thunderstorms as it lifts the moist and unstable warmer air.

If the warmer air is moist and stable then, as it is forced upward it expands and cools, forming stratus clouds.

For pilots, the effect of the passage of a cold front depends on the stability of the warmer air. If this is unstable then severe turbulence, heavy rain and reduced visibility can occur ahead of the front. If it is stable, then rain or even freezing rain (depending on the temperature of the cooler air mass) can occur just

[10] See section 4.10 for a description of stability: in summary unstable air will tend to continue to rise once it has been lifted.

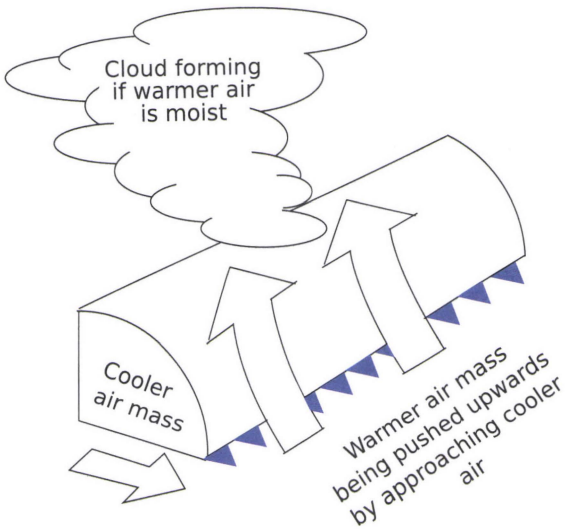

Figure 4.18: Cross-section Through a Cold Front

behind the front. In either case, an observer in the warmer air mass will see:

- the pressure, which has been dropping as the front approached, start to climb
- the air temperature drop and
- the winds veer as the front passes through.

Exercise 22 *Consider the following (slightly abbreviated but genuine) METARs from Winnipeg.*

```
CYWG 102351Z 03014KT 10SM SCT200 09/03 A3015
CYWG 102251Z 03013KT 10SM BRK200 12/04 A3012
CYWG 102209Z 04019KT 10SM SCT070 15/05 A3009
CYWG 102151Z 31014KT 10SM SCT070 18/01 A3008
CYWG 102051Z 29012KT 10SM BRK085 18/03 A3007
CYWG 101951Z 27014KT 10SM BRK090 19/04 A3008
CYWG 101851Z 28012KT 10SM OVC090 17/06 A3009
CYWG 101751Z 28010KT 10SM BRK050 17/06 A3010
```

During the time covered by these METARs a cold front passed through Winnipeg: what characteristics of the frontal passage can be found in the METARs?

Warm Front

A warm front occurs when a warmer (not necessarily warm!) air mass moves and overruns a cooler (not necessarily cold!) air mass—see figure 4.19. As the warmer air overruns the cooler air it moves upwards, expands and cools. If it is moist then clouds and precipitation will form, the precipitation falling through the cooler air below and what started as rain in the warmer air may turn to snow, ice pellets or freezing rain before reaching the ground. A warm front therefore represents one form of a temperature inversion—the air may be warmer rather than cooler aloft.

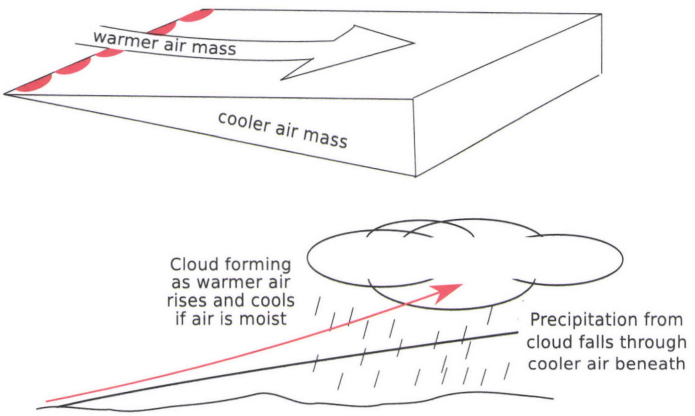

Figure 4.19: Cross-section Through a Warm Front

The zone between the two air masses is quite shallow and the slope of a warm front is normally quite low (about 1 in 100). The warm air therefore spreads for a significant distance in front of the line where the warmer air is at ground level and reaches up to the tropopause—see figure 4.20.

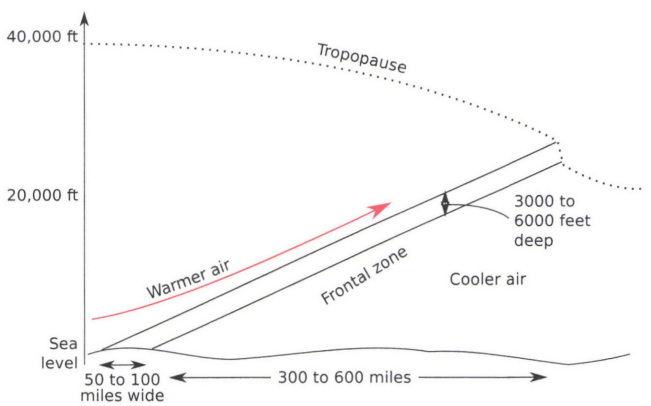

Figure 4.20: The Frontal Zone

To an observer on the ground in the cooler air, the approaching front can be identified by the cloud types: initially high cirrus and then cirrostratus, altostratus, nimbostratus and possibly stratus and fog, the cloud levels descending as the front approaches. As the front approaches, the atmospheric pressure also drops. As it passes, the air temperature rises, the winds veer and the drop in pressure stops.

Stationary Front

A stationary front occurs at the boundary between two air masses when neither is strong enough to move the other. Stationary fronts tend to remain immobile for several days with the boundary line oscillating backward and forward in waves. The weather at a stationary front is not as well defined as at a cold or warm front but it often includes thick nimbostratus clouds (often with bases around 1,000 ft AGL and tops at 18,000 ft ASL or higher) with the associated precipitation.

Eventually a stationary front will either become a cold or warm front, as one or the other air mass starts to move, or will change into a shear line: a narrow area across which there is a major change in wind direction. A stationary front becomes a shear line when the temperature difference across the frontal boundary disappears while the wind shift persists. This occurs most often over the ocean where the temperature of the water is the same on both sides of the frontal boundary and modifies the air masses on either side of it to correspond to its own temperature.

On surface analysis charts, stationary fronts are marked as alternating red half-circles (pointing towards the cooler air mass) and blue spikes (pointing towards the warmer air mass).

As with other fronts, a change in temperature and wind direction occurs as the front is crossed.

4.7.2 Frontal Dynamics

Figure 4.5 on page 61 shows an over-simplified view of the arctic and polar fronts. In practice, the two air masses are continually "fighting" for supremacy: the colder air to the north pushing southwards, undercutting the warmer air, and the warmer air pushing northwards, riding over the cooler air. As these interactions occur, the different speeds of the air cause wind shear and this, combined with the Coriolis Effect (see section 4.6.4), causes the air at points along the polar front to start to rotate and a low pressure area to form. Figure 4.21 shows this happening at points along the polar front: kinks form in the polar front and the cooler air starts to move southwards (blue triangles) while the warmer air moves northwards (red semi-circles).

Figure 4.22 illustrates one of the "kinks" in more detail. Generally the cold front will move more quickly than the warm front and figure 4.23 shows it catching up. As can be seen from the top part of that figure, the colder air mass is moving south-eastward, undercutting the warmer air, while the warmer air is moving north-westwards riding over the cooler air—rotation is intensifying around the low pressure.
Because the cold front is moving more quickly, it will eventually catch up with the warm front as shown in figure 4.24. When this occurs, the cooler air undercuts the warmer air, but its behaviour depends on its temperature relative to the cold air over which the warmer air is climbing. If the approaching cooler air is warmer than the cold air mass then it too will climb over it, as shown in figure 4.24. If it is cooler it will undercut the cold air mass. Either way the warmer air no longer reaches the surface and no warm front is represented on a surface analysis chart—a **trowal** or *TRough Of Warm air ALoft* has formed. A trowal is indicated on a surface analysis chart by the single arrow-head symbol shown in figure 4.24.

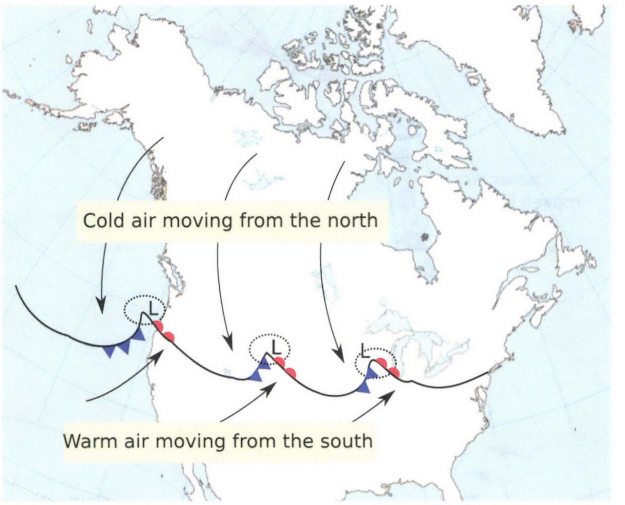

Figure 4.21: Tensions Along the Polar Front

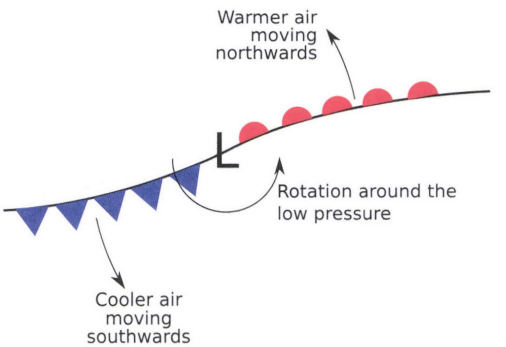

Figure 4.22: Front Formation: Stage 1

Figure 4.24 shows one of the two possible ways in which the trowel can form: this is illustrated again in the lower part of figure 4.25. However, if the approaching air mass causing the cold front is colder than the air mass to the north (i.e., if the air is colder at Ⓐ than at Ⓑ in figure 4.24) then it will undercut it as shown in the upper part of figure 4.25. In either case an *occlusion* forms as the warm air is no longer in contact with the ground.

Note that while this rotation is occurring around the

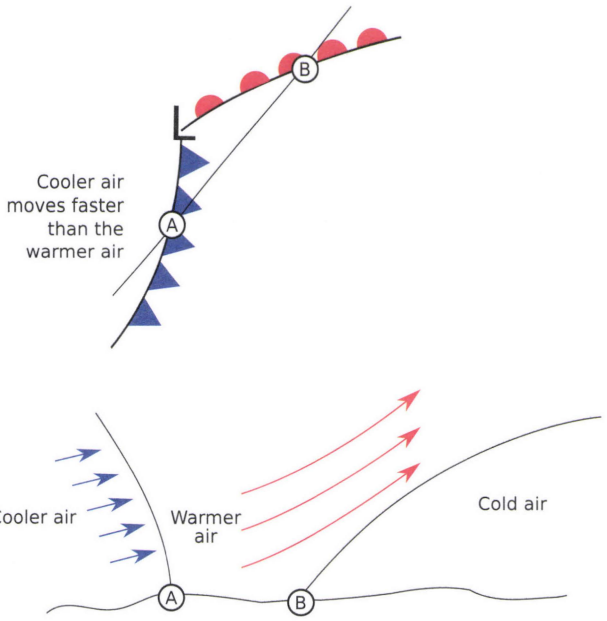

Figure 4.23: Front Formation: Stage 2

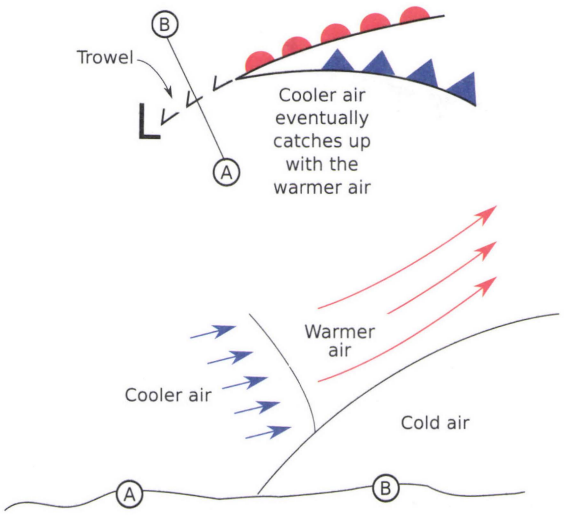

Figure 4.24: Front Formation: Stage 3

area of low pressure, the entire system will be moving eastward.

Figure 4.26 illustrates the formation of a trowal on a genuine forecast: it can be seen that the cold front is travelling at 25 knots, while the warm front is travelling at 10 knots. In the upper part of the figure, the colder air has already started to undercut the warmer air, forming a trowel (shown just to the north of the L).

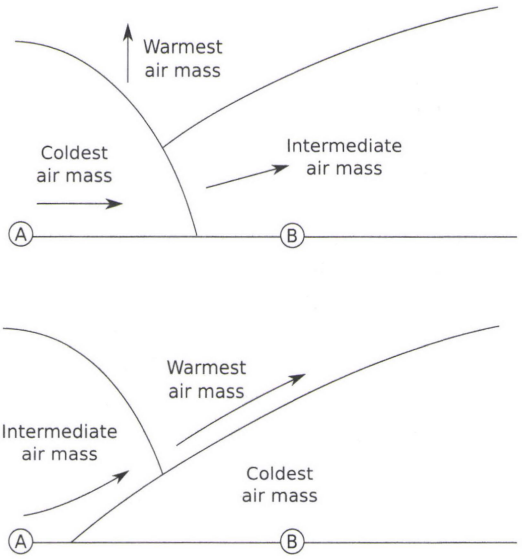

Figure 4.25: Structure of a Trowal

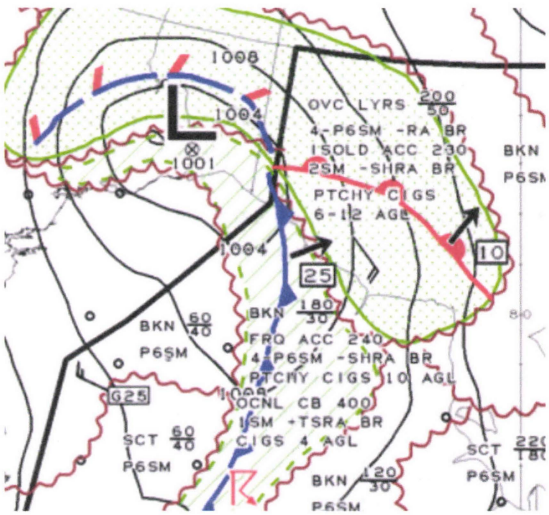

Figure 4.26: Trowal Forming

4.8 Altimetry

4.8.1 Density Altitude

For a description of density altitude, see section 11.4.2 on page 241.

4.8.2 Altimeter Settings

As described in section 10.1.4 on page 207, the barometric altimeter is simply a barometer measuring atmospheric pressure. As an aircraft climbs, the atmospheric pressure diminishes and this is displayed by the altimeter. Since the sea-level atmospheric pressure changes constantly, it is important to know its current value in the area where the aircraft is flying so that its

altimeter can be correctly set. This value is given in inches of mercury in aviation weather reports and, at all times, you must be sure that the value in the altimeter is set correctly: otherwise the altimeter could be over- or under-reading, causing you to fly at the wrong altitude.

4.8.3 Effects on Flight

Whenever there is a change in the sea level pressure in the area where an aircraft is flying, a barometric altimeter will misread until it is adjusted.

If the sea level pressure *increases,* the altimeter will think that it is lower than it really is (because higher pressure normally occurs lower in the atmosphere) and will under-read.

If the sea level pressure *decreases,* the altimeter will display a reading higher than the correct altitude.

Exam Hint 7 *Remember the tag: "High to Low, Watch out Below".*

Both of these conditions are dangerous: the former can cause you to fly too high, possibly breaking an altitude assigned by ATC, and the latter can cause you to think that you are higher than you actually are, possibly causing controlled flight into terrain.

The barometric altimeter is sensitive not only to changes in atmospheric pressure, but also to changes in temperature. Flying from an area of higher to an area of lower temperature also causes the altimeter to over-read: see section 4.5.4.

The moral is to ensure that you adjust your altimeter to local conditions frequently and that you make the necessary cold temperature corrections when flying an approach. Generally, ATC will provide altimeter settings along your route of flight and at your destination aerodrome.

Exercise 23 *You fly from Winnipeg, St Andrews (760 ft ASL) to Thunder Bay (653 ft ASL). You correctly set your altimeter before leaving Winnipeg where the altimeter setting is* 30.45″ *Hg. You forget to adjust the altimeter before landing in Thunder Bay where the altimeter setting is* 29.91″ *Hg. What does your altimeter read when you are on the ground in Thunder Bay?*

4.9 Moisture

4.9.1 Relative Humidity & Dew Point

Before reading this section it might be useful to review the descriptions of partial pressure and (saturated) vapour pressure given in section 4.1.3.

One of the constituents of the atmosphere is water vapour—typically less than 1% by mass: see figure 4.27 which illustrates the maximum proportion of the atmosphere that water vapour can form. The ratio

$$R = \frac{p}{p^*} \times 100\%$$

is known as the relative humidity, where p is the partial pressure of water vapour in the atmosphere and p^* is the saturated vapour pressure of the water vapour at the particular temperature. Thus, if the air is completely saturated with moisture ($p = p^*$), the relative humidity is 100%. If the air is completely dry ($p = 0$), then the relative humidity is 0%.

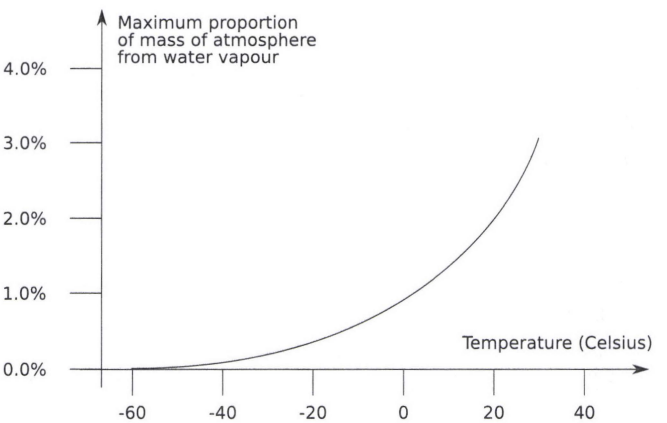

Figure 4.27: Water Vapour in Saturated Air at Sea Level

Relative Humidity is measured in an automated weather station (such as an AWOS: see page 94) by using an electrical capacitor[11] constructed to use the air as part of its insulating (dielectric) layer. Different amounts of water vapour in the air cause its capacitance to change and these changes can be measured and converted into a relative humidity reading.

If the pressure of a parcel of air is held constant and the air is cooled, a temperature will be reached where the relative humidity is 100%—the air is completely saturated. This temperature is known as the **dew point**. The difference between the dew point and the actual temperature is a measure of the air's humidity. The highest dew point ever recorded was 35°C in

[11] A capacitor consists of a piece of insulation sandwiched between two conductors. As the insulation changes, so does the "capacitance" of the capacitor: something that can be measured electrically.

Dhahran, Saudi Arabia at 15:00 local time on 8th July 2003. The temperature at the time was 42°C.

Clearly, given the current temperature and dew point it should be possible to calculate the relative humidity (certainly if the temperature is equal to the dew point then the relative humidity is 100%). The actual formula is quite complex but, for relative humidities above about 50% there is a simple approximation:

$$R = 100 - 5 \times (T - T_d) \tag{4.2}$$

R is the relative humidity, T the actual temperature and T_d the dew point.

Exercise 24 *The METAR for an airport indicates that the temperature is 28° C and the dew point 20° C. What is the approximate relative humidity at the airport?*

4.9.2 Change of State

Matter exists in four states: solid, liquid, gas and plasma. Although plasmas are the most common form of matter in the universe, they only exist at very high temperatures and are not relevant for meteorology. For any substance, a liquid contains more energy (heat) than a solid and a gas contains more energy than a liquid. The names given to the changes of state are listed in table 4.28 and, with the possible exception of sublimation and deposition, these are all familiar words. Sublimation and deposition are described in the next section.

Latent heat is required for melting, sublimation and evaporation and latent heat must be removed for freezing, condensation and deposition.

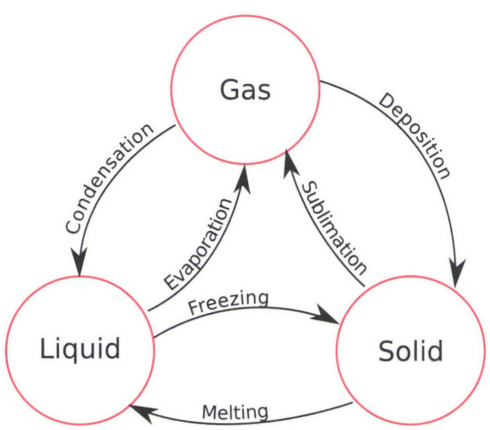

Figure 4.28: State Changes

4.9.3 Sublimation/Deposition

Sublimation is a transition from a solid to a gas without an intermediate liquid stage. Most Canadians have seen this occur on very sunny days in winter when snow (solid) disappears (forms a gas) without passing through a liquid state (water). At the molecular level, the pressure of the atmosphere is too small to prevent the molecules of the solid, excited by the heat of the sun, escaping directly and forming a gas.

The opposite of sublimation is deposition: where a gas becomes a solid without the intervening liquid state. Frost appearing on the wing of an aircraft left standing outside overnight is an example of deposition—there was no liquid (water) phase.

4.9.4 Lapse Rates

Before reading this section, it may be useful to reread the description of the adiabatic process and latent heat in section 4.1.3.

A **lapse rate** is a measure of how temperature changes with height. There are several lapse rates of interest to pilots:

The **environmental lapse rate** is the actual rate at which temperature changes with altitude at a particular place at a particular time. This is typically measured either by releasing a balloon fitted with temperature, pressure and humidity sensors from the ground, or by carrying such a device on a commercial aircraft. In either case, the readings are transmitted to an observer on the ground. The environmental lapse rate in the ISO standard atmosphere (section 4.2.2) is 1.98 Cdeg per 1,000 ft. As with other aspects of the standard atmosphere, this is very rarely the environmental lapse rate in the real atmosphere.

Note that this lapse rate has nothing to do with parcels of air rising and cooling. As described in section 4.3.1, the atmosphere is generally warmed from the earth and, within the troposphere, the atmosphere becomes cooler with height.

The **adiabatic lapse rate** is the rate at which the temperature of a parcel of moist or dry air changes as it rises through the atmosphere.

For air that is not saturated with moisture, this is straightforward and cooling occurs as the outside air pressure drops and the parcel of air expands. As explained in section 4.1.3, such an expansion causes cooling. Unless heat enters or leaves the parcel (and air is a poor conductor of heat), non-saturated air will cool at 3 Cdeg per 1,000 ft. This is known as the **Dry Adiabatic Lapse Rate.**

For a parcel of air saturated with moisture, the situation is more complicated because two effects are fighting each other:

1. Because of expansion, the parcel cools in the same way that dry air does—at 3 Cdeg per 1,000 ft.
2. As the parcel cools, water vapour turns into liquid water (fog, cloud, etc.) and, in doing so, releases latent heat (see section 4.1.3). This warms the parcel of air, offsetting some of the 3 Cdeg per 1,000 ft cooling.

Given these two conflicting energy exchanges, the actual cooling varies between 1.2 Cdeg per 1,000 ft at 26°C and 2.2 Cdeg per 1,000 ft at −10°C. This is known as the **Saturated Adiabatic Lapse Rate.**

The two adiabatic lapse rates are illustrated in figure 4.29. Note that the dry adiabatic lines simply indicate a constant drop of 3 Cdeg per 1,000 ft; the saturated adiabatic lines are slightly curved. These curves appear on a Skew-T chart as illustrated in figure 5.12 and described in section 5.4.4 on page 104.

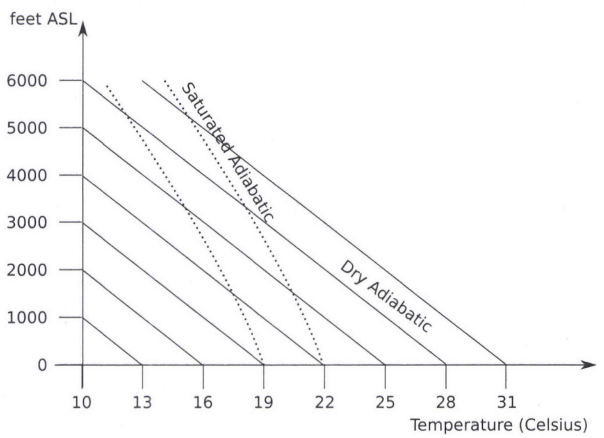

Figure 4.29: Adiabatic Lapse Rates

Exam Hint 8 *Students often confuse the environmental and adiabatic lapse rates.*

Remember that the environmental lapse rate has nothing to do with packets of air expanding and cooling: it is simply a measurement of how the atmosphere cools with altitude above the warm earth. The standard environmental lapse rate is 1.98 Cdeg per 1,000 ft.

The adiabatic lapse rate has nothing to do with the atmosphere cooling with altitude. It is a measure of how the temperature of a parcel of air changes as the parcel expands or is compressed. For non-saturated air, the standard rate is 3 Cdeg per 1,000 ft and for saturated air it is between 1.2 and 2.2 Cdeg per 1,000 ft.

4.9.5 Cloud Formation

Figure 4.30 contains two diagrams, both simplified versions of figure 4.29—only one of the saturated adiabatic lines remains and only one dry adiabatic line is shown. The difference between the two pictures is the relative humidity: in the leftmost diagram there is a 10 Cdeg spread between the temperature and the dew point; in the rightmost only 5 Cdeg. The rightmost diagram represents a much more humid day.

In the left-hand diagram, the surface temperature is 29°C and the dew point is 19°C. As shown in the diagram, the dew point reduces slightly at higher altitudes. Consider a parcel of air containing moisture (but not saturated) at sea level with a temperature of 29°C and imagine that this parcel of air starts to rise. As it rises, it will expand, expending energy as it pushes against the outside air, and thereby cool at the dry adiabatic lapse rate of about 3 Cdeg per 1,000 ft. By the time it reaches just over 4,000 ft ASL, its temperature (just under 19°C) will have become the same as the dew point. As it continues to rise and cool, its water vapour will condense, causing clouds. The cloud base will therefore form at just over 4,000 ft.

In the rightmost diagram the dry adiabatic lapse rate and dew point lines meet at about 2,500 ft ASL, indicating that the bases of cumulus clouds will be no lower than that.

As a rule of thumb, valid at least during the morning and early afternoon when the temperature is not dropping, the lowest bases of cumulus clouds in feet can be found by multiplying the difference between the air temperature and the dew point by 400. If there is a significant amount of turbulence in the air then the bases will actually be higher than this.

Exercise 25 *Your local airport is reporting a temperature of 29° C and a dew point of 19° C. What is the lowest height above ground that cumulus clouds are likely to form?*

Anecdote 14 *I began flying as a glider (sail-plane) pilot flying in the Black Mountains in Wales. On some summer days the sky was cloud-free as there were no parcels of air rising until their moisture condensed into cumulus cloud. On days such as this we would get the tow-plane (a Piper Pawnee) to fly low over the edge of the ridge of the mountains. This would disturb the air sufficiently for parcels of it to start rising. Seeing cumulus clouds forming immediately behind the tow-plane in otherwise clear air was a wonderful demonstration of cloud formation in action.*

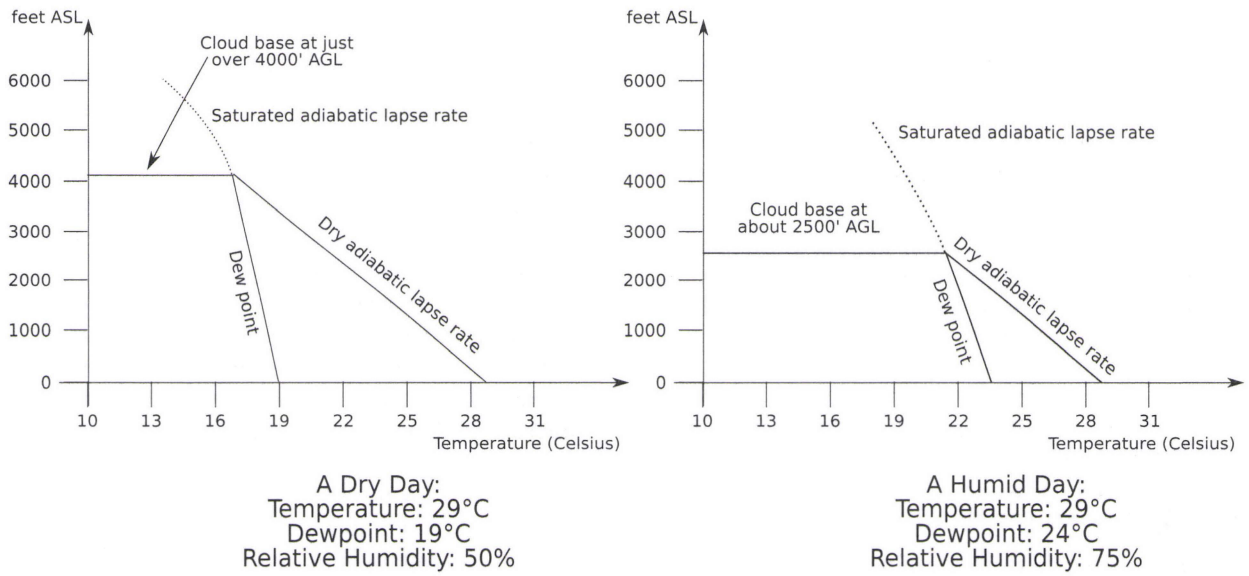

Figure 4.30: Cumulus Cloud Base Estimation

The description above illustrates one way in which saturation occurs: the temperature of the air drops until it reaches the dew point. Another way of reaching saturation is for the amount of water vapour to increase while the temperature remains constant. When water vapour condenses onto the bathroom mirror when you take a shower, this is not because the temperature has dropped (in fact, unless you take cold showers, it has probably increased), but because the dew point has been raised. In the atmosphere, this can occur, for example, if rain falls from a higher cloud but evaporates before reaching the earth (such rain is known as **virga**). This evaporating rain can increase the humidity (and, of course, slightly reduce the surrounding temperature as it absorbs latent heat). Water vapour can also be added to the air through evaporation from lakes, oceans or large rivers.

Even if the air temperature and dew point are the same, a cloud will not form unless nuclei are present in the atmosphere around which the water droplets can condense. Over land these nuclei are normally very small dust particles (generally less than 0.001 mm in diameter) and over the sea they are often salt particles from spray that has evaporated. Smoke from forest fires or volcanoes is an excellent source of nuclei. Sometimes, to invoke precipitation deliberately, the air is "seeded" with chemicals such as silver iodide to act as condensation nuclei.

4.9.6 Precipitation

Precipitation (rain, snow, hail, sleet, etc.) occurs when condensation has happened and the water droplets coalesce around some larger form of nucleus.

Condensation by itself is not enough to cause precipitation—it simply forms a cloud. Within a fair-weather cumulus cloud, for example, the water droplets are only about 0.005 mm in diameter. Their speed of falling through the cloud is much less than the speed of the air rising within the cloud and consequently no rain falls from the cloud. When condensation droplets coalesce within a cloud, they increase in weight and eventually start to fall as precipitation.

Precipitation can be divided into three categories:

1. liquid water: rain (drops larger than 0.5mm in diameter), drizzle (drops smaller than 0.5mm in diameter)
2. supercooled liquid water that freezes on contact with the surface: freezing rain
3. ice: snow, snow pellets, hail (typically 5mm to 50mm in diameter although one hailstone of 178mm has been recorded in the USA), ice pellets (with diameters less than 5mm)

4.10 Stability & Instability

Three types of stability are described in section 9.8.2 on page 194: positive, negative and neutral stability. In meteorology, positive stability in the atmosphere is known as **stable air** and negative stability is known as **unstable air**.

4.10.1 Lapse Rate & Stability

In practice, the standard environmental lapse rate (change in temperature at higher altitudes) of 1.98 Cdeg

per 1,000 ft is rarely met. The actual lapse rate is the primary determinant of the stability of the air.

To see how the environmental lapse rate determines stability, consider a parcel of air at sea level where the temperature is 15°C.

We will consider two circumstances: in the first the environmental lapse rate will be higher than standard: 4 Cdeg rather than 1.98 Cdeg per 1,000 ft; in the second the lapse rate will be lower than standard: 1.5 Cdeg per 1,000 ft.

1. **High Lapse Rate**—Unstable Air

   In this case the environmental lapse rate is 4 Cdeg per 1,000 ft. Because we're assuming that the temperature is 15°C at sea level, the temperature at altitude drops as listed in the second column of figure 4.31. If the parcel of air at sea level (at 15°C) were somehow to start moving upwards (see section 4.10.5), then it would expand and cool. By the time it had reached 1,000 ft, it would have cooled by the standard dry adiabatic lapse rate, 3 Cdeg, and be at 12°C, 1 Cdeg warmer than the surrounding air. This is unstable: a parcel of air warmer than its surroundings, being less dense, will continue to rise even if the mechanism that caused it to start to rise disappears. As it rises from 1,000 ft to 2,000 ft it will again expand and cool by 3 Cdeg: it will be at 9°C, now 2 Cdeg warmer than its surrounding. The process is clear: a parcel of air that starts to rise will always be warmer than its surroundings and will continue to rise, accelerating as it goes. This type of air is said to be **unstable**.

2. **Low Lapse Rate**—Stable Air

   In this case the environmental lapse rate is $1\frac{1}{2}$ Cdeg per 1,000 ft. Since it is 15°C at sea level, the temperature at altitude will drop as listed in the third column of figure 4.31. If the parcel of air at sea level (at 15°C) were somehow to start moving upwards, then it would expand and cool. By the time it had reached 1,000 ft, it would have cooled by the standard dry adiabatic lapse rate, 3 Cdeg, and be at 12°C, 1.5 Cdeg cooler than the surrounding air. This is stable: a parcel of air cooler than its surroundings, being more dense, will have no inclination to continue rising unless the mechanism that started its upward motion persists. Under normal circumstances it will simply settle back towards the ground. This type of air is said to be **stable**.

   An extreme case of stability occurs when the temperature actually increases with height: a so-called *inversion*—see section 4.3.3.

Altitude	Temperature (4 Cdeg/1000ft)	Temperature ($1\frac{1}{2}$ Cdeg/1000ft)
8000	−15.0°C	3.0°C
7000	−11.0°C	4.5°C
6000	−7.0°C	6.0°C
5000	−4.0°C	7.5°C
4000	−1.0°C	9.0°C
3000	3.0°C	10.5°C
2000	7.0°C	12.0°C
1000	11.0°C	13.5°C
Sea Level	15.0°C	15.0°C

Figure 4.31: High and Low Lapse Rates

4.10.2 Modification of Stability

The stability of the atmosphere is changing all the time. Warming at the surface or cooling at high levels can increase the lapse rate and thereby cause the air to become more unstable. Similarly, surface cooling or warming of the air aloft causes increased stability.

4.10.3 Stable & Unstable Air

Unstable air, caused by a higher-than-normal environmental lapse rate, is characterised by a bumpy ride as the aircraft flies through the rising parcels of air. As you curse the bumpiness of your ride, remember that glider pilots deliberately seek out these rising parcels of air to gain lift.

Cumulus clouds are an indication of instability and, in extreme cases, the rising air can cause cumulonimbus clouds to form with their associated thunderstorms—see section 4.15. However, a clear sky does not necessarily mean that there is no unstable activity. The instability might be there, but the air may be too dry for clouds to form—this phenomenon is called "blue thermals" by glider pilots.

To gauge the stability of the air, you should keep note of the change in outside air temperature as you climb.

Stable air, in contrast, leads to a smooth ride as there is no vertical air movement. Often, though, stable air results in poor visibility because there is no movement to dissipate smoke and dust particles.

4.10.4 Surface Heating/Cooling

The surface of the earth is heated in two ways: by the radiant heat from the sun (during the day) and from the atmosphere. The earth cools by losing heat to the atmosphere (which convects it away) and, when the night sky is clear, by radiation into space.

4.10.5 Lifting Processes

As described in section 4.10.1, unstable air manifests itself when something causes a parcel of air to start rising. As described in anecdote 14 on page 77, sometimes the lifting agent is human. There are, however, various natural lifting mechanisms:

- **Unequal Heating.** If part of the ground becomes warmer than its surroundings, then so will the air immediately above it. That warmer air, being less dense than its surroundings, will then start to rise. For example, a black road in an otherwise green and brown landscape will often absorb more of the sun's rays and become warmer than its surroundings.
- **Orographic Lifting.** If the wind moves across a plain until it meets a range of hills, it will have to start moving upwards. If the air is stable then the wind will simply drop down on the other side of the hills; if it is unstable then the air will continue to rise: see figure 4.32.
- **Frontal Lifting.** As described in section 4.7.1 on page 71, a cold front can undercut warmer air and force it upwards. Similarly, warmer air at a warm front rises over the cooler air. This is typically less violent than the lifting caused by a cold front.
- **Convergence.** At the centre of a region of low atmospheric pressure, winds blow inwards, thereby forcing the air to rise.
- **Mechanical Turbulence.** Winds blowing across obstacles on the ground cause turbulence in the lower layers: see section 4.13.2. This turbulence is sometimes enough to start an upward movement. Anecdote 14 refers to mechanical turbulence caused by an aircraft.

4.11 Clouds

Clouds provide visible signs of the actual and potential future weather—being able to interpret the clouds allows you to assess the amount of turbulence, possible dangers from icing, visibilities and other significant factors that could affect your flight. Remember that even in the more populated areas of Canada, weather reporting stations are spread out and NAV CANADA's forecasts are, of necessity, based on incomplete data. Your ability to analyse the weather ahead of your aircraft from your observations of the clouds may provide you with the best prognosis.

One of the most entertaining books about clouds is *The Cloudspotter's Guide* by Gavin Pretor-Pinney, founder of the *Cloud Appreciation Society*. The whole of the last chapter of that book is dedicated to the "Morning Glory", the most impressive stratocumulus in the world that sometimes appears in the Southern Hemisphere's Spring (September and October) over the Gulf Savannah region of northern Queensland, Australia. Glider pilots from all over the world converge on Burketown to surf this cloud.

4.11.1 Classification

The first person to try to classify the clouds and name each type was an amateur British meteorologist called Luke Howard in 1802. He coined the terms:

- "cumulus" to mean "heaped" for clouds that develop vertically
- "stratus" to mean "layered" for clouds that spread into a horizontal layer
- "cirrus" to mean a "curl of hair" for very high clouds consisting of ice crystals
- "nimbus" to mean "rain bearing"

Together with the term "alto" to mean "middle-level",[12] these classifications work, up to a point. For example, you would expect cirrostratus clouds to be layered, rather than vertically developed, clouds found at high level. And you would be right. However, many other cloud types do not fit with this classification scheme: fog, mist, contrails, billow clouds, mammatus, orographic and pileus clouds. And since we have nimbostratus clouds, why are nimbocumulus clouds called cumulonimbus? The most confusing of all is stratocumulus since "stratus" and "cumulus" are normally mutually exclusive.

Figure 4.33 summarises the main types of cloud. These are described in section 4.11.3 below.

4.11.2 Formation & Structure

As described in section 4.9.5, clouds appear when the temperature of the air matches its dew point and nuclei are present around which the water droplets can form. This can occur if the temperature falls to the dew point while the humidity remains constant or if the humidity rises (e.g., from virga or from evaporation from a lake or river), raising the dew point to the current temperature.

[12] If you are familiar with Latin it may surprise you that *alto* is used to mean *middle-level* rather than *high*. The term was chosen by meteorologists, presumably with poor Latin, in 1855 and has never been changed.

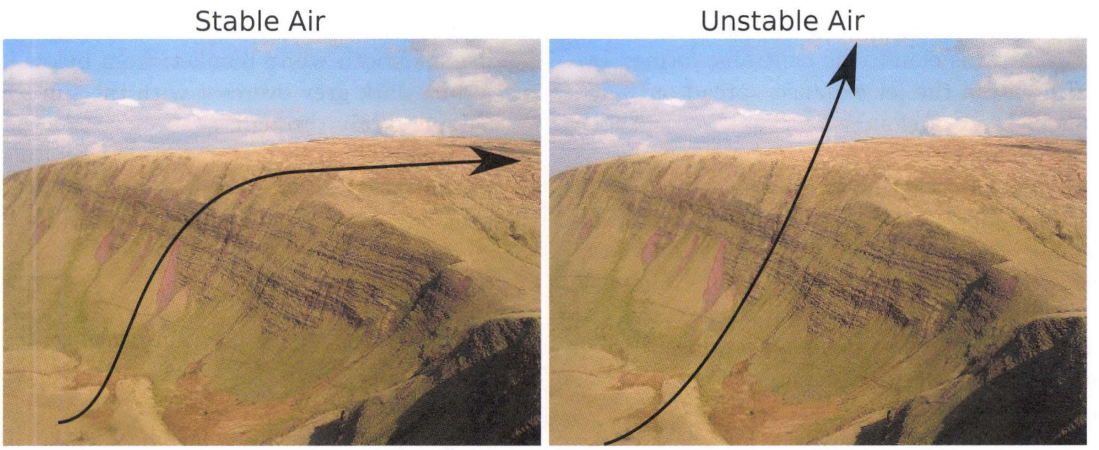

Figure 4.32: Orographic Lift in Stable and Unstable Air

Level	Cloud Type
High (above 20,000 ft)	Cirrus Cirrocumulus Cirrostratus
Middle (6500 to 20,000 ft)	Altocumulus Altocumulus Castellanus Altostratus Nimbostratus (Extends into high level)
Low (below 6500 ft)	Cumulus Cumulus Fractus Cumulus Congestus Cumulonimbus (Extends through all levels) Stratus Stratus Fractus Stratocumulus

Figure 4.33: The Basic Cloud Types

4.11.3 Types & Recognition

The cloud types listed in figure 4.33 are described in the sections below.

Cirrus

Cirrus is the highest type of cloud. Cirrus clouds are created from ice crystals and although they create precipitation, that precipitation always evaporates long before it reaches the ground. Any of the cirrus family of clouds (cirrus, cirrocumulus and cirrostratus) can create the "halo" phenomenon around the moon on a clear night.

Cirrus clouds trap and reflect heat back downwards towards the earth but they also reflect incoming sunlight, preventing it from reaching the ground. It has not yet been decided whether their net effect is to warm or cool the earth.

If the conditions are right, the position of the jet stream (see section 4.6.13) can be determined from the ground by watching the stream of cirrus cloud as it sweeps along.

Cirrocumulus

Cirrocumulus clouds create what is often called a *mackerel sky.*[13] Cirrocumulus tends to appear in patches rather than cover the whole sky and although the patches may appear continuous from the ground, they actually consist of individual clouds.

The appearance of cirrocumulus is often taken as a harbinger of bad weather as it indicates a significant amount of moisture at the top of the troposphere and strong high-level winds.

Cirrostratus

Cirrostratus are high, thin clouds with a milky, almost transparent, appearance. They form a continuous layer extending over a very large area, often when cirrus clouds spread and join together.

Anecdote 15 *Cirrostratus clouds have had their impact on world history. At the battle of Milvian Bridge on 28th October 312, a cross of light appeared to the army of the Roman Emperor Constantine. This inspired his army to win the battle and Constantine established Christianity as the religion of the Roman empire. Almost certainly the "cross" they saw was caused by the refraction of the sun's rays through the ice crystals in a cirrostratus cloud.*

[13] Apparently named by sailors after the markings on a King Mackerel.

Contrails from high-flying aircraft are another generator of cirrostratus cloud: the contrails, formed by the freezing of liquid in the jet exhaust, spread out and form a continuous layer of cloud.

Cirrostratus clouds often form optical phenomena. More common than Constantine's cross is the appearance of "sundogs": additional points of light that form on each side of the sun. This may be the origin of the poem *Die Nebensonnen* by Wilhelm Müller famously set to music by Franz Schubert in his *Winterreise* cycle.[14] The actual optical phenomenon produced by cirrostratus depends on the precise shape of the ice crystals it contains.

Altocumulus

Altocumulus consists of round clumps of clouds, normally formed from water droplets and sometimes from ice crystals.

One particularly beautiful and characteristic form of altocumulus is the lenticular (or lens-shaped) cloud that forms when wind is forced upwards by meeting a mountain range. The rising air expands and cools and a smooth, lens-shaped cloud forms indicating the position of a mountain wave. As the air descends on the downwind side of the mountain it is again compressed and heated: the cloud disappears. One characteristic of altocumulus lenticularis by which it can be recognised is that it remains stationary, however hard the wind is blowing. Lenticular clouds caught on photographs, particularly at night, have often been mistaken for visitors from other planets: see figure 4.34 for a particularly clear UFO.

For the pilot of a glider, lenticular clouds indicate lift: rising air that can be used by the glider to gain height. For pilots of powered aircraft the same sign indicates turbulence: rising air and, moments later, descending air. The other significant factor for a pilot is the drop in atmospheric pressure that occurs on the downwind side of the mountain—causing altimeters to over-read.

Lenticular clouds are often associated with another special type of altocumulus—the *Rotor Cloud* (also sometimes called *Roll Cloud*). These form downwind of the mountain in the low pressure area as the wind is sucked downwards and starts to rotate. Rotor clouds indicate severe turbulence.

Altostratus

Altostratus is a mid-level, rather featureless cloud that spreads across a large part of the sky. It consists of a mixture of water droplets and ice crystals, the proportions of each depending on its temperature. From above, particularly if there are no higher clouds, it looks like a smooth white blanket; from below it appears to be a dull, dark grey overcast with the sun sometimes shining dimly through.

Generally, altostratus does not produce appreciable precipitation although if it is particularly thick, light rain, snow or ice pellets can fall from it.

Nimbostratus

Nimbostratus clouds are rain-bearing (hence the *nimbo* part of the name). They are generally dark, thick enough to block the sunlight, and have ragged bases. They consist of a combination of water droplets, ice crystals and snowflakes, depending on their temperature. Although they are *stratus* clouds, they can be very thick: often extending from around 1,000 ft to 18,000 ft.

Cumulus

Cumulus clouds are low, detached, vertically-developed, puffy clouds consisting of water droplets. In *The Cloud Spotter's Guide*,[15] Gavin Pretor-Pinney shares his calculation that a moderately-sized cumulus cloud has a mass of about 200,000 kg (about the mass of eighty elephants). Normally cumulus clouds are scattered randomly across the sky but sometimes they align into "streets" (more correctly *cumulus radiatus*) parallel with the wind.

For glider pilots, cumulus clouds mark out areas where the air is rising—areas where their glider could also obtain lift. Glider pilots are particularly keen to see cloud streets because these indicate directions in which lift can be guaranteed for a considerable distance. For pilots of powered aircraft, cumulus clouds indicate turbulence.

As cumulus clouds decay, their edges become less distinct and they are termed *cumulus fractus*, meaning "broken".

Cumulonimbus

When the atmosphere is moist and unstable, cumulus clouds can have large vertical spreads. Towering cumulus is an intermediate form between a fair-weather cumulus (known officially as a *cumulus mediocris*) and the cumulonimbus. Figure 4.35 shows an example of a towering cumulus.

The cumulonimbus is the thundercloud—see section 4.15. Its base can be as low as 2,000 ft above the ground and its top flattening into an anvil shape of ice crystals against the tropopause.

Cumulonimbus clouds are indicators of very strong up- and down-drafts, hail, lightning and intense rain and

[14] The poem begins (loosely translated): "I saw three suns close to each other in the heavens".

[15] ISBN 0-340-89589-6

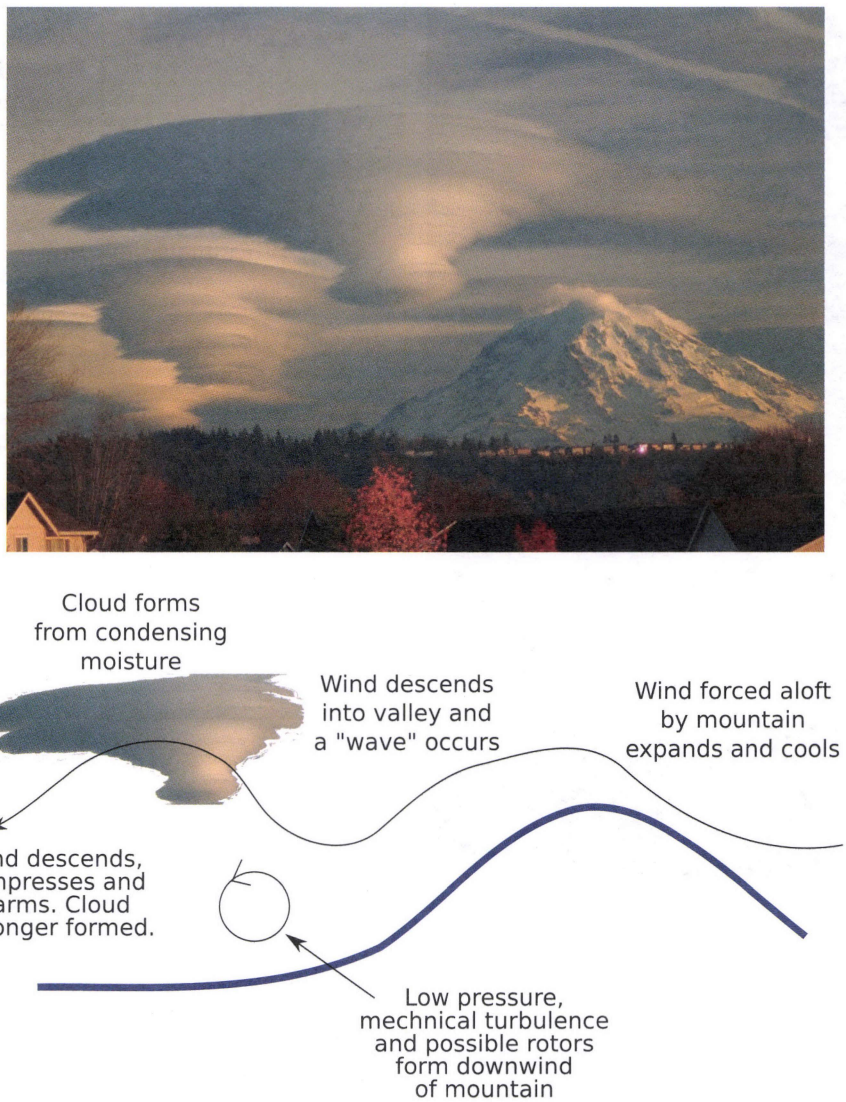

Figure 4.34: Lenticular Cloud (Tim Thompson, Sumner WA., Mt Rainier, 5th Dec 2008)

are therefore a serious threat to aircraft of all sizes. Although any individual cumulonimbus is unlikely to persist for more than an hour, often several form in close proximity to each other.

Stratus

Stratus is effectively a lower-level version of the altostratus: a featureless, horizontally-spread layer of cloud with few features.

To the VFR pilot, stratus can mean waiting for days for the sky to clear. For an IFR pilot it means a short and smooth flight through the thin layer of cloud to bright and smooth conditions on top.

Anecdote 16 *Many years ago, I decided to get an IFR rating after my wife and I spent several days in a small town in New Brunswick waiting for an overcast layer of stratus to break up. The overcast was at about 1,000 ft AGL and clearly not very deep but my VFR-only licence did not permit a departure. The delights of the town were exhausted in the first half day and it was a* very *long wait to get out.*

Stratus cloud can have its base at ground level. It is then called **fog** or **mist**: see section 4.12.1.

Stratus Fractus

Stratus fractus consists of stratus cloud broken into patches with shapes that continually change.

Figure 4.35: Towering Cumulus (Alison Hobbs)

Stratocumulus

Stratocumulus clouds form as a stratus layer breaks up, with gaps forming in the previously continuous layer. The sun's rays reach the earth through the gaps and cause local heating which may start local convective activity, creating vertical development of the clouds.

For pilots, the danger of stratocumulus clouds is the possibility of the formation of towering cumulus or even cumulonimbus clouds *embedded* within the largely unbroken stratus layer—see figure 4.42. It is normally easy to spot these turbulent and dangerous clouds when they are isolated but, without sferics equipment (see section 10.5.3 on page 224) or an uplink weather service on board the aircraft, a pilot may blunder into an embedded towering cumulus or cumulonimbus while flying in stratocumulus.

4.11.4 Precipitation & Turbulence

See figure 4.36, but note that only cumulonimbus and nimbostratus clouds *invariably* produce precipitation.

Cloud Type	Precipitation Reaching Ground	Turbulence
Cirrus	None	Moderate
Cirrocumulus	None	Moderate
Cirrostratus	None	Moderate
Altocumulus	None	Lenticular indicates turbulence
Altostratus	Rain, Drizzle, Ice Pellets	Light
Nimbostratus	Rain, Drizzle, Ice Pellets	Light
Cumulus	Rain, Snow, Snow Pellets	Moderate
Cumulonimbus	Rain, Hail, Snow	Severe
Stratus	Rain, Drizzle	None
Stratus Fractus	Rain, Drizzle	
Stratocumulus	Rain, Snow, Snow Pellets	Moderate

Figure 4.36: Precipitation and Turbulence in Cloud

4.12 Surface-Based Layers

The World Meteorological Organisation (WMO) issues, amongst many other publications, a classification of surface-based layers that reduce visibility. This classification includes fog, ice fog, steam fog, mist, haze, smoke, volcanic ash, dust, sand and snow. This section describes a few of these.

4.12.1 Fog Formation

Fog is simply stratus cloud at ground level. For fog to occur, moist air must be cooled by the ground below its dew point. This is, however, not *sufficient* for the formation of fog—you will have noticed dew and even frost forming on cool ground without there being any accompanying fog. Other conditions, as described below, must also pertain. The basic types of fog are as follows.

Radiation Fog. This occurs when the sky is clear and the ground loses heat rapidly through radiation into space. This cools the air in the first two or three hundred feet of the ground and, if it is moist, condensation and fog results. For radiation fog to form, winds must be very light. Therefore this type of fog often occurs in valleys protected from the wind, when the air is particularly moist. Katabatic winds (see section 4.6.10) will often dissipate this type of valley fog.

Advection Fog. This occurs when warm, moist air moves horizontally over a cooler surface, propelled either by a wind or by a warm front. Unlike radiation fog, advection fog can occur when the wind is strong. It often occurs at sea when warm air is blown over a cold ocean or on land when warm, moist air is blown across ground covered with snow.

Canada has the honour of hosting the foggiest place in the world: the Grand Banks off Newfoundland where advection fog forms at the meeting of the cold Labrador Current from the north and the warmer Gulf Stream from the south.

Upslope Fog. This forms when a moderate wind blows up a slope. If the wind is strong then the mechanical turbulence will cause stratus or stratocumulus cloud to form but, with a moderate wind, the air expands as it rises, cools and forms fog.

Steam Fog. This is perhaps the most beautiful of all the types of fog: it forms above a body of water and makes it appear that the lake or river is steaming. It forms when cool air is blown gently over water that is much warmer. The lowest layer of air warms quickly and absorbs some of the moisture. Being warmer than the air above, it starts to rise, expands, cools and the water vapour condenses out again. In the arctic this type of fog is called **arctic smoke** or *sea smoke*.

Freezing Fog. This consists of small particles of supercooled water that freeze on contact with any surface. It occurs when the air close to the surface is below 0°C and winds are very light.

Precipitation or Frontal Fog. When rain falls into dry air below a cloud, the water droplets sometimes evaporate into water vapour (known as **virga**). If the temperature conditions are suitable, the air saturates and condensation (fog) forms.

4.12.2 Mist

For aviation meteorology purposes, if the horizontal visibility through the ground-based layer is less than 5/8 SM (1 km), then the cloud is called fog, otherwise it is called mist.

4.12.3 Haze/Smoke

Unlike fog, which is caused by water droplets, haze is caused by dust, smoke and other dry particles that obscure visibility. Sources of haze particles include farming (ploughing in dry weather), traffic, industry, volcanic ash and wildfires. Haze is particularly prevalent when the atmospheric conditions prevent dispersion—light winds and stable air. It occurs particularly when there is a temperature inversion with altitude.

4.12.4 Obstruction to Vision

Although not "surface-based layers", blowing snow or volcanic dust also obscure vision.

4.13 Turbulence

Turbulence occurs when the smooth flow of the wind is disturbed in some way, causing horizontal wind shear. The following sections list the primary causes of turbulence.

4.13.1 Convection

In the 1960s there was a vogue for Lava Lamps—ornaments containing a coloured liquid and blobs of wax; see figure 4.37. A heater in the base of the lamp warmed the wax which, becoming less dense, rose to the top of the lamp where it cooled and descended again. Although these lamps are now out of fashion, they provided a very clear illustration of convection in action.

Figure 4.37: Convection (Novemberchild)

Within the atmosphere, localised heating of the ground (e.g., of a dark-coloured road) causes the air

immediately above to become less dense than its surroundings and start to rise. As it rises it expands and cools and eventually starts to descend again. Unless the air is moist and a cumulus cloud forms, there is nothing to indicate this area of rising and descending air although, if it could be seen, it would look very much like the lava lamps.

Glider pilots seek out these patches of rising air (called **thermals**) and use them to provide lift. When no cumulus clouds form to mark the position of the thermals they are known as *blue thermals*. For pilots of powered aircraft, they represent areas of turbulence: as you fly on a sunny day imagine that you are flying across the lava lamp entering and leaving the globs of rising and descending wax.

Normally, convective turbulence dissipates at a few thousand feet above the ground.

4.13.2 Mechanical

Mechanical turbulence occurs when the smooth flow of the wind is disrupted by man-made or natural ground features. The most severe mechanical turbulence occurs when the wind passes over mountains, but buildings or small hills close to a runway can be particularly dangerous when the wind is in the wrong direction. See figure 4.34 on page 83 and figure 4.38.

When the mechanical turbulence is caused by mountains then it is known as **orographic** turbulence. In this case lenticular and rotor clouds may form.

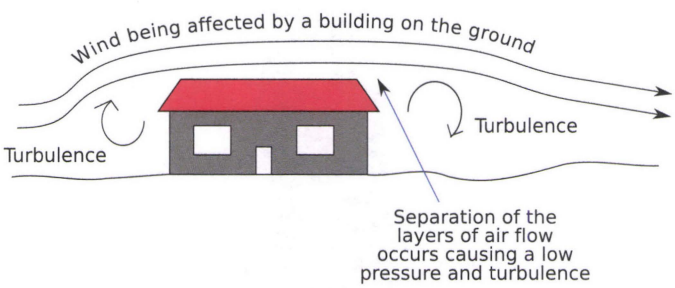

Figure 4.38: Mechanical Turbulence from a Building

Generally, the stronger the wind, the greater the friction with the objects on the ground and the greater the turbulence. If the winds are gusting, then friction with the ground will exaggerate the mechanical turbulence.

4.13.3 Wind Shear

Wind shear (see page 69) also generates turbulence.

4.13.4 Clear Air Turbulence

Clear Air Turbulence (CAT) is, by definition, turbulence when there are no clouds to mark its presence—if you see a large cumulus cloud ahead then you can expect turbulence as you enter the convective region; with CAT there is no visible warning of its presence.

Clear-air turbulence is caused by high-level wind shear, typically between 23,000 and 39,000 ft ASL, often in the proximity of a jet stream. As there are no associated clouds, special devices known as *scintillometers* or *Doppler LIDARs*[16] have to be fitted to aircraft to detect CAT—see page 224.

4.13.5 Reporting Criteria

When reporting turbulence in a Pilot Report (PIREP)—see section 5.3.4 on page 100—you should use the descriptions listed in figure 4.39 together with *occasional* (less than $\frac{1}{3}$ of the time), *intermittent* (between $\frac{1}{3}$ and $\frac{2}{3}$ of the time) or *continuous* (more than $\frac{2}{3}$ of the time). When reading PIREPs of turbulence make sure that you understand the type of aircraft from which the report was made—moderate turbulence reported by a Boeing 777 is not the same as moderate turbulence reported by a Cessna 150.

Turbulence above 15,000 ft which is not associated with cumulus cloud (including thunderstorms) should be reported as *clear air turbulence.*

Exercise 26 *You are flying a Piper Arrow and are experiencing turbulence in cloud which, at irregular and widely-spaced intervals of some minutes, causes you to have to change the aircraft's attitude to retain altitude. You are in no danger of losing control of the aircraft but it is uncomfortable both for you and your passengers. ATC asks you to report on the turbulence you are experiencing. How would you respond?*

4.14 Aircraft Icing

Section 11.8.9 on page 253 lists some of the dangers of aircraft icing, including the loss of lift, the locking of control surfaces, loss of thrust, tailplane stalls and loss of radio contact through the icing of antennæ. This section describes the types of icing that may form on an aircraft.

4.14.1 Types of Icing

The ice that adheres to the external surfaces of an aircraft is categorised as:

[16] Light Detection and Ranging.

Type	Effect on Aircraft	Effect on Passengers
Light Chop	Slight, rapid and somewhat rhythmic bumpiness without appreciable changes in altitude or attitude	Slight strain against seat belts. Unsecured objects move slightly.
Light Turbulence	Momentarily slight, erratic changes in altitude and/or attitude	
Moderate Chop	Rapid bumps or jolts without appreciable changes in altitude or attitude.	Definite strain against seat belts or shoulder harnesses. Unsecured objects are dislodged. Food service is difficult.
Moderate Turbulence	Changes in altitude and/or attitude occur but the aircraft remains in positive control at all times. Some changes to airspeed.	
Severe	Large, abrupt changes in altitude and/or attitude and airspeed. The aircraft may be out of control for a few moments.	Forced violently against seat belts or shoulder harnesses. Unsecured objects are tossed about. Food service and walking are impossible.
Extreme	Violent tossing about with the aircraft almost impossible to control. May cause structural damage.	

Figure 4.39: Turbulence Reporting Criteria

Clear or glaze ice which is smooth and initially follows the surface on which it forms (e.g., the top surface of a wing). However, after heavy accumulation, it can form ridges.

Clear ice forms most often in freezing rain below nimbostratus cloud: liquid water below 0°C which freezes on impact with the aircraft. Before a supercooled water droplet can freeze, its latent heat has to be given up and this gives the water time to flow backward over the surface before it freezes. The amount of latent heat to be lost and the amount of flow backward across a surface is most when the water droplets are close to 0°C and less when they are cooler.

Clear ice can alter the aerodynamic shape of airfoils dramatically and reduce or destroy their effectiveness. It is difficult to remove and, if it does break away, large chunks may cause damage by hitting other parts of the airframe.

Rime ice which has a rough, milky-white appearance, being a mixture of tiny ice particles and trapped air. It occurs in high altostratus or altocumulus cloud when the airframe is below 0°C and tiny, supercooled liquid water droplets freeze on contact. Because the droplets are small, rime ice does not form continuous sheets as clear ice may. Rime icing can form in temperatures between 0°C and −40°C, but is most common in the range from −10°C to −20°C.

Mixed ice which is a combination of rime and clear ice. This is the most common form of airframe icing and results from the different moisture droplet sizes encountered in cloud: large drops produce clear ice and small droplets produce rime ice.

Hoar Frost which is a white crystalline coating that can usually easily be brushed off. It is normally encountered when an aircraft is parked outside overnight. The skin of the aircraft cools to below 0°C and, as moist air passes over it, the water vapour changes directly into ice through deposition. Hoar frost can also occur in flight if an aircraft flies from freezing temperatures into warmer moist air—for example, on descent or when climbing through a temperature inversion.

Hoar frost does not alter the aerodynamic shape of the wing in the manner in which clear ice does but it disrupts the smooth airflow over the wing, causing separation of the airflow over the upper surface. It is particularly dangerous during takeoff when the flow disturbance may prevent the aeroplane from becoming airborne.

4.14.2 Where does Icing Occur?

Pilots often ask whether there is a temperature below which icing is unlikely to occur. Clearly at some temperature there will be no moisture left in the air, it all having solidified into ice, and so no airframe icing can occur. Figure 4.40 is taken from *The Aircraft Icing Handbook* published by the CAA in New Zealand in 2000. Note that the vertical motion in a convective (cumulus) cloud tends to carry the water droplets higher and increase their size, giving this type of cloud a higher risk of producing icing at lower temperatures than stratus clouds.

Prob. of Icing	Cloud Type	
	Cumulus	Stratus
High	0°C to −20°C	0°C to −15°C
Medium	−20°C to −40°C	−15°C to −30°C
Low	Below −40°C	Below −30°C

Figure 4.40: Probability of Icing by Temperature

Another useful tool for predicting where ice can occur is the Appleman diagram: see figure 4.41. This reflects old (1954) research by Herbert Appleman which has been updated by many researches since. It remains, however, a useful guide for the probability of meeting icing in cloud. Figure 4.41 relates the relative humidity at different temperatures with the observed likelihood of icing. It is found that about 50% of all pilot reports of icing occur when the temperature and dew point lie in Area A. A further 20% occur in Area B and only 10% in Area C.

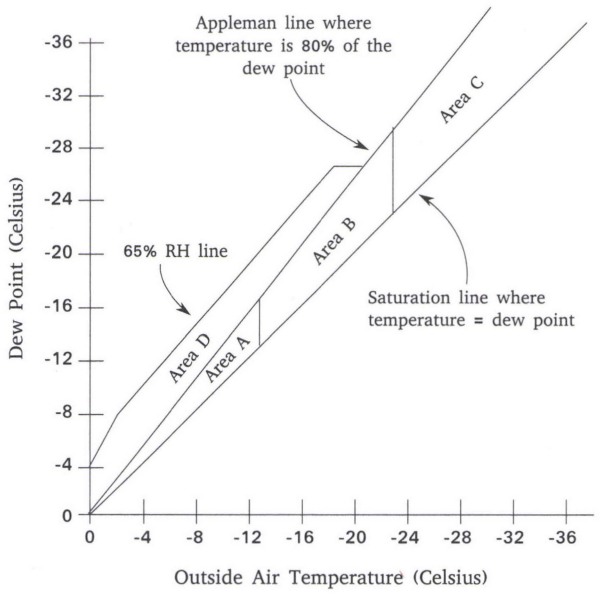

Figure 4.41: The Appleman Diagram

Updating Appleman's work, Paul Schultz and Marcia Politovich published *"Toward the improvement of aircraft icing forecasts for the continental United States"* in 1992 and report that 87% of pilot-reported icing occurred at temperatures from 0 to −20° C where the relative humidity was greater than 50%.

During the first decade of the 21st Century, Environment Canada carried out a number of flight studies on the characteristics of in-flight icing using a specially-equipped Convair-580. These studies led to a number of very interesting results including:

- the observed thickness of layers of super-cooled water droplets capable of creating ice on an aircraft. This information is of obvious use to a pilot trying to escape icing. The result was that the mean depth of icing was 2,200 ft and the median depth was 1,600 ft.

- the comparison of the temperatures at the top and bottom of ice-forming clouds. This is of importance for a pilot deciding whether to climb or descend to get out of the icing. In 17% of cases, the temperature at the top of the cloud was warmer than the temperature at the bottom.

Icing is dangerous and I would encourage all pilots to read the Environment Canada reports, particularly *"A study of vertical liquid water profiles of clouds from in-situ measurements"*.

4.14.3 Where does Ice Form?

Ice forms most readily on sharper components such as thin leading edges, fins, antennæ and propeller blades. This occurs because air tends to stagnate in front of blunt objects, increasing the ambient pressure and thus increasing the temperature. Airspeed also influences the rate of ice accretion, the higher the speed (below about 250 knots) the faster ice accumulates. Kinetic heating due to skin friction between the air stream and the aircraft's fuselage and wings at speeds above 250 knots reduces the risk of icing significantly.

4.14.4 Reporting Icing

In the same way that standard terms are defined for reporting levels of turbulence, there are standard terms for defining the amount of ice that is being encountered:

- **trace:** ice is accumulating slightly faster than it is sublimating, but it is not hazardous and de-icing does not have to be deployed.

- **light:** ice is accumulating faster than it is sublimating and de-icing will have to be deployed after an hour.

- **moderate:** either de-icing must be deployed or a diversion made to get out of the icing conditions.
- **severe:** the rate of accumulation is such that the de-icing equipment cannot cope and an immediate diversion must be made to get out of the icing conditions.

4.15 Thunderstorms

4.15.1 Development

Thunderstorms require three things to develop:

1. **Moist air.** As mentioned in the description of *latent heat* on page 57, it is the latent heat released when the water vapour condenses that provides the energy for the thunderstorm. The article on thunderstorms in the Encyclopedia Britannica estimates that, in an "average" thunderstorm, about 50,000,000 kg of water are lifted and the energy released amounts to about 10,000,000 kilowatt-hours (3.6×10^{13} joules), which is equivalent to a 20-kiloton nuclear warhead.
2. **Unstable air.** If the air is unstable (see section 4.10) then, once it has started to rise, it will continue to rise—creating the massive updrafts required to keep a thunderstorm fed with incoming air.
3. **A lifting agent.** Something needs to start the lifting process. For isolated thunderstorms this might be local heating causing convection. A more effective agent is an approaching cold front undercutting warmer air and making it lift. This tends to create lines of thunderstorms along the front. One particularly dangerous type of lifting is illustrated in figure 4.42—in this case the approaching cold front is catching up with the warm front and is driving the warmer air aloft. In doing so, convection is being added to the stratus cloud normally associated with a warm front and cumulonimbus cloud is forming, embedded in the stratus. Being embedded, it is not visible to pilots, particularly when they are flying in IMC, and the only means of detecting it from the ground is by the use of echo tops radar (see section 5.3.3 on page 98).

To become severe, thunderstorms also need significant (but not too much) wind shear aloft. Without this wind shear, a so-called **pulse thunderstorm** forms. In this case the downdraft falls close to the updraft, reducing its momentum and cutting off the inflow of air. It is in predicting the likely strength and duration of a thunderstorm that the hodograph, introduced in section 4.6.12 on page 69, can be useful by providing a visualisation of the wind shear. When the hodograph is more or less a straight line (e.g., the upper chart in figure 4.15), the most likely development is the storm splitting into two cells, forming mirror images of each other, one rotating clockwise and moving to the right, the other rotating anticlockwise and moving to the left. However, the increasing directional and speed shear, as shown in the lower part of figure 4.15 is likely to produce a supercell thunderstorm. This continues until the shear becomes very pronounced when it again hinders the development of an intense storm. The use of the hodograph to predict the strength of thunderstorms is discussed in much greater length in the 1991 paper *A Review for Forecasters on the Application of Hodographs to Forecasting Severe Thunderstorms* by Charles A. Doswell of the National Severe Storms Laboratory, USA.

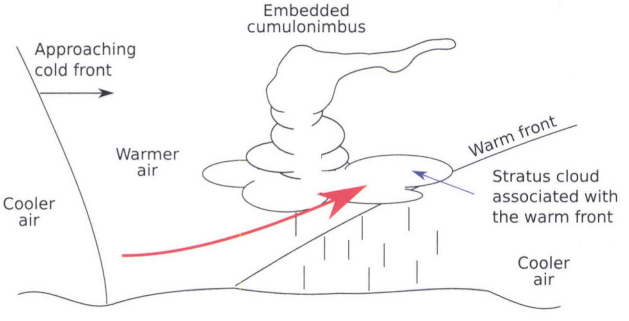

Figure 4.42: Embedded Cumulonimbus

4.15.2 Life Cycle

A thunderstorm passes through three overlapping phases:

1. **Cumulus stage.** Every thunderstorm starts as a cumulus cloud when moist, unstable air is lifted. The air expands and cools (although it is still warmer than its surroundings) and water droplets condense, releasing latent heat. This additional energy accelerates the rising air and vertical speeds of 3,000 ft per minute are common.
2. **Mature stage.** The air continues to rise until it reaches air which is warmer than it is, typically at the tropopause. Instead of continuing to rise, the air is forced to spread out, providing the anvil shape. Figure 4.43 shows this happening from a very unusual viewpoint—from above. The photograph, taken from the International Space Station as it passed over western Africa near the Senegal-Mali border, shows a fully-formed anvil cloud with numerous smaller cumulonimbus towers rising near it.

As the thunderstorm matures, the water droplets coalesce into larger and heavier droplets and freeze to become ice particles. Depending on the strength of the wind shear aloft, the droplets may be held aloft long enough to form as hail or may melt as they fall and become rain. The falling precipitation creates strong downdrafts and, if the wind shear has separated the updrafts and downdrafts, then severe turbulence occurs, creating strong winds, frequent lightning and even tornadoes.

When the downdraft reaches the ground it spreads out, creating rapid changes in the direction and strength of the wind at and near ground level.

The mature stage of a thunderstorm typically lasts between 15 and 30 minutes.

3. **Dissipating stage.** In this stage the downdraft starts to dominate. As the cool air in the downdraft spreads out on the ground it cuts off the warmer air flowing into the thunderstorm. The updraft therefore disappears and the thunderstorm dissipates.

4.15.3 Types of Thunderstorm

As described above, one of the requirements for a thunderstorm to form is some form of lifting agent to start the convective activity. Thunderstorms are classified as *Air Mass* thunderstorms if this lifting action arises from local heating or orographic lift within an airmass. If the lifting agent is a frontal system then they are known as *Frontal* thunderstorms. Clearly frontal thunderstorms are easier to predict than air mass ones since frontal systems can be tracked.

4.15.4 Hazards

The hazards associated with thunderstorms are many and include:

- severe turbulence caused by the updrafts and downdrafts.
- hail. This occurs during the mature stage when the updrafts are particularly strong. If the wind shear aloft is strong then the hail may fall some distance from the centre of the storm.
- intense rain.
- lightning. The effect of a lightning strike on an aircraft can be hardly noticed or catastrophic. The article *What happens when lightning strikes an airplane?*[17] by Edward J. Rupke contains an estimation that, on average, each aircraft in the U.S. commercial fleet is struck by lightning more than once each year. In fact, aircraft often trigger lightning when flying through a heavily charged region of a cloud. Initially, lightning attaches to an extremity such as the nose or wingtip. The aircraft then flies through the lightning flash, which re-attaches itself to the fuselage at other locations before leaving at some other extremity, such as the tail. For aircraft with metal fuselages, most of the current from the lightning discharge remains on the exterior of the aircraft. Aircraft with composite fuselages have an embedded layer of conductive fibres or screens to carry lightning currents. Although lightning strikes have caused structural failure of aircraft, their major impact is on the aircraft's electrical and avionics systems. Commercial airliners and larger general aviation aircraft are now being manufactured with High-Intensity Radiated Field (HIRF) protection and various reports[18] indicate that this is very effective in preventing lightning damage to these systems.
- poor visibility.
- sudden reduction in temperature caused by the downdrafts.
- sudden decreases in pressure caused by the updrafts. This, of course, causes the aircraft's altimeter to over-read although, if you are caught in a thunderstorm, that may be least of your worries.
- severe icing.

Outside the thunderstorm itself, the gust fronts associated with it can cause significant wind shear within several thousand feet of the ground.

Anecdote 17 *"Doc" Saundby, the instructor most responsible for turning me into a pilot, described being caught close to a thunderstorm in a glider. With the spoilers fully deployed and the nose pointing downwards, he was carried upwards at a thousand feet per minute and was extremely lucky to be thrown out of the updraft at 17,000 ft ASL.*

4.15.5 Squall Lines

As described in section 4.6.7, a squall is a sudden and violent change in the wind. A **squall line** is a narrow,

[17] Scientific American, 14th August 2006.

[18] e.g., *General Aviation Lightning Strike Report and Protection Level Study*, report DOT/FAA/AR-04/13 from the Office of Aviation Research, Washington, DC, USA.

Figure 4.43: An Unusual View of a Cumulonimbus Cloud (NASA)

and highly mobile, line of thunderstorms of the type normally associated with a cold front. Sometimes, however, squall lines form well away from a frontal system.

Squall lines are classified as either *progressive* or *serial*. Progressive squall lines are relatively short and curved, oriented at right angles to the wind whereas serial squall lines tend to be several hundred kilometres in length and form almost parallel with the wind. Either of these types of squall line is extremely dangerous for aircraft, but serial squall lines tend to do more damage to structures on the ground.

4.15.6 Tornados

The inflow of air into thunderstorms can be violent. If the inflowing air already has rotation then the rotation may be intensified, forming a concentrated vortex from ground level into the medium levels of the storm. The width of the vortex ranges from about 75 metres to over a kilometre. The winds in these vortices can reach speeds of 200 knots and the pressure inside the vortex is very low. If the vortex reaches the ground it is known as a tornado, if it reaches a body of water it is known as a water spout and if it reaches neither then it is known as a funnel cloud. It is unlikely that any aircraft could penetrate one of these vortices without sustaining structural damage.

4.16 Answers to Exercises

This section gives answers to the exercises in this chapter.

Exercise 19

If a vacuum is placed above it, water in the well will rise because of the atmospheric pressure pressing down on the remaining water—as in figure 3.1. So, if the well were full of mercury (rather than water), on a standard day a pump could suck it up only 29.92 inches (76cm). Water is 13.6 times less dense than mercury and so can be sucked up 13.6 times further, but even that is only about 34 ft (10.3m). Your well would possibly just work on very high pressure days (greater than 30.9 inches of mercury) but not otherwise.

Exercise 20

The difference in pressure between the H and L is $1023 - 995 = 28$ hectopascals. Since the points are 150 nm apart, the average pressure gradient is $\frac{28}{150} = 0.19$ hectopascals per nautical mile.

Exercise 21

The two aerodromes are approximately 300 nautical miles apart and so the values in the second column of figure 4.10 apply. The sea level pressure at

Lloydminster is forecast to be 1020 hectopascals. The sea level pressure at The Pas is more difficult to assess but because it lies between the 1028 and 1032 hectopascal isobars, we can assume a value of 1030. The pressure difference between the two aerodromes is therefore forecast to be 10 hectopascals. The pressure gradient is therefore 10 hectopascals per 322 nautical miles or 3.1 hectopascals per 100 nautical miles.

To apply figure 4.10 to find the approximate wind speed the latitudes of Lloydminster and The Pas are needed. The CFS indicates that both of these lie at about 53°N so we should use a multiplication factor slightly larger than 2.4: simple interpolation yields the value of 2.44 (see appendix D on page 349 for details of interpolation). The wind speed is therefore about $2.44 \times 10 = 24.4$ knots.

At the time covered by the GFA in figure 4.11, the upper winds at Saskatoon, a little south of a line between Lloydminster and The Pas, were forecast to be 22 knots.

Exercise 22

The passage of a cold front typically causes:

- the atmospheric pressure, that has been falling as the front approached, starting to climb. This occurs between 20:51Z and 21:51Z in the METARs.
- the air temperature to drop as the station passes into the cooler air mass. There is a sudden drop in temperature recorded in the METARs, starting at about 21:51Z.
- the wind to veer. As can be seen from the METARs, the wind which has been blowing from the west suddenly veers to the north east just after 21:51Z.

All of these tend to indicate that the cold front passed through Winnipeg at about 21:51Z.

Exercise 23

You have flown from a higher-pressure to a lower-pressure area without adjusting your altimeter. It will therefore be over-reading (indicating than you are higher than you really are). The difference in pressure is $(30.45 - 29.91) = 0.54''$ Hg. Using an aviation calculator, the difference in altitude corresponding to $0.54''$ Hg can be found to be 496 ft (without such a calculator $1.0''$ Hg can be assumed to be roughly equivalent to 1,000 ft and an approximation of 540 ft can be derived). So the altimeter will be over-reading by 496 ft—it will be reading 1,149 ft. Clearly such an over-reading altimeter could be extremely dangerous when descending into Thunder Bay, given the hilly terrain in the area.

Exercise 24

Using equation 4.2 on page 76:

$$\begin{aligned} R &= 100 - 5 \times (T - T_d) \\ &= 100 - 5 \times (28 - 20) = 60 \end{aligned}$$

So the relative humidity is about 60%.

Exercise 25

Using the rule of thumb given in the text, the bases are likely to be at or above $400 \times (29 - 19) = 4000$ ft.

Exercise 26

Using figure 4.39, you appear to be experiencing moderate turbulence. However, it is not continuous and so would be reported as *occasional moderate turbulence.*

Chapter 5

Weather Reports & Forecasts

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Chapter 4 describes the complexity of our earth's atmosphere. Working from reports of weather conditions from all over the world, meteorologists model the atmosphere in order to predict what the weather in a particular area will be. Once the reports have been processed and the forecasts produced, they have to be disseminated to pilots. This chapter outlines how the reports and forecasts are produced, describes the various agencies that pilots can use to obtain weather information and the formats of the reports and forecasts published by the meteorologists.

The Transport Canada written examination only covers forecasts and reports issued by NAV CANADA, whereas many forecasts issued in the USA also cover parts of Canada and are useful for flight planning, particularly the Skew-T charts covered in section 5.4.4.

5.1 Accessing Weather Data

5.1.1 Flight Service Stations

Flight Service Stations (FSSs) exist at many medium-sized airports across Canada. The personnel in these stations provide the *Aviation Weather Information Service* (AWIS): they are permitted to read weather forecasts and reports and describe radar images to a pilot on request but are not authorised to interpret the information or provide weather briefings.

In addition, Flight Service Station personnel provide airport advisory services.

5.1.2 Flight Information Centres

Four Flight Information Centres (FICs) exist across Canada: at Kamloops, Edmonton, London and Québec City. Each of these, except for London, covers the part of the country in which it is situated. The FIC at London also covers most of the east of Canada.

Flight Information Centre personnel provide an *Aviation Weather Briefing Service*, not only reading printed information to a pilot, but also offering interpretation of the data. The FIC personnel also provide *en route* weather information (including local altimeter settings), handle flight plans, provide fully interpretive weather briefings and issue and co-ordinate NOTAMs.

Each of these FICs can be reached from anywhere in Canada by telephone by dialling 1-866-WX-BRIEF (English) or 1-866-GO-METEO (French) and selecting the appropriate option. One problem with using these numbers with a cellular telephone is that they route according to the area code of the telephone rather than the location whence the call is being made—in these circumstances it is probably better to dial the local FIC directly using the toll-free number in the CFS. Making contact from a cellular telephone is particularly difficult in the USA. Contacting local flight services, on the

USA's equivalent number of 1-800-WX-BRIEF, can't always be done using a Canadian cellular telephone.

5.1.3 Aviation Weather Website

NAV CANADA administers a website[1] from which graphical and textual weather information related to a particular aerodrome or route of flight can be retrieved.

The website also gives access to SIGMETs, PIREPs, NOTAMs, infrared and visible satellite images and both ECHOTOP and CAPPI radar images. A pilot can set filters on NOTAMs that are displayed (e.g., to exclude NOTAMs about obstruction lights or NOTAMs about cranes).

5.1.4 PATWAS

Until 2016, the *Pilot's Automatic Telephone Weather Answering Service* or PATWAS was, as its name suggests, an automated system through which a pilot could obtain a recorded message of weather reports and PIREPs at a particular aerodrome, at aerodromes along a particular route or at aerodromes in a particular geographic area. The service was discontinued in November 2016.

5.1.5 Automatic Terminal Information Service (ATIS)

At busy aerodromes, the pilots of incoming and outgoing aircraft all need the same basic information: the weather conditions including the altimeter setting, the runways in use, any important aerodrome NOTAMs, etc. Rather than the controllers having to read this information to each pilot, an Automatic Terminal Information Service (ATIS) is often provided. This is a continuous broadcast of recorded information.

The ATIS recording is identified by a letter, updated whenever the recording changes; a new recording is normally issued every hour or whenever some significant meteorological event occurs. When approaching an aerodrome with an ATIS, you should inform ATC of the identifier letter of the ATIS you have heard: this indicates to ATC that you have the basic information.

Anecdote 18 *Be very careful to note the issue time of the ATIS. I was once flying to North Bay, Ontario, in solid cloud. I listened to the ATIS when I was about 30 minutes out and was building a picture of the weather when I realised that the ATIS was two and a half hours old—it had simply not been updated. I told ATC and a new ATIS appeared five minutes later.*

[1] `https://plan.navcanada.ca/wxrecall/`

The frequency of the ATIS broadcast is contained in the aerodrome's CFS entry.

5.1.6 VOLMET (HF) Broadcast

VOLMET is a system of radio transmitters broadcasting weather forecasts, information about significant weather patterns and weather reports on the High Frequency (short wave) bands between 2MHz and 17MHz. These can be received by aircraft in flight over the ocean outside the range of VHF shore-based transmissions.

5.2 Report & Forecast Data

The sources listed above make weather reports (what is the weather doing *now*?) and forecasts (what is the weather likely to do *later*?) available to a pilot. These can only be as accurate as the methods used to take observations and build forecasts. This section describes in outline the origins of these methods.

5.2.1 Taking Observations

Weather observations may be made by:

- trained human observers either on the ground (see section 5.3.2) or in the air (section 5.3.4), or
- by machines: weather radar (section 5.3.3) or an AWOS or LWIS as described in the following sections.

Automated Weather Observation Station (AWOS)

An AWOS is a system that, without manual intervention, measures meteorological conditions and broadcasts them on a radio frequency that can be found in the CFS. There are many types of AWOS, but almost all measure cloud height and amount of cloud cover (below a certain level), visibility, precipitation, icing, temperature, dew point, wind speed and direction and altimeter setting. Newer AWOSs include density altitude, thunderstorm reporting and, where Runway Visibility Range (RVR) equipment is installed, runway visibilities.

Limited Weather Information System (LWIS)

An LWIS is similar to an AWOS, in that it makes an automatic broadcast of weather conditions, except that it only reports temperature, dew point, wind speed and direction and altimeter setting. Some of the more modern LWISs also report density altitude.

Accessing AWOS & LWIS Information

AWOSs and LWISs broadcast their reports on a radio frequency using an automated voice. In Québec and the National Capital these broadcasts are in French or English on different frequencies. Elsewhere they are in English. The reports are also available on the NAV CANADA website.

Limitations of AWOSs & LWISs

There is a limit on the height and coverage of cloud that an AWOS or LWIS can detect. Generally any cloud above 12,000 ft AGL is not detected and, because the device can only look directly upwards, it has to average the cloud cover over a period of time. If no cloud is detected, some AWOSs and LWISs will report this as "sky clear below twelve thousand feet", but others simply report "sky clear".

There are also types of weather phenomena for which no sensors exist, including hail and ice pellets.

5.2.2 How are Forecasts Built?

This section describes some of the meteorological models used to create the forecasts that pilots consult. The details of these models would not appear on a Transport Canada examination, but this is useful background information when reading a forecast, giving an insight into why forecasts are sometimes wrong. Note that the results of the models are available on the Internet and may be studied by pilots as well as meteorologists, particularly when flying in the USA.

The primary inputs to forecasts are observations. These may be surface-based reports such as METARs, or higher-level observations from radar, PIREPs, balloons, satellites or equipment fitted into airliners. These observations are fed into predictive mathematical models. There are two types of model: dynamical and statistical.

Dynamical Models

A dynamical model consists of a three-dimensional grid of points (see figure 5.1) covering a particular geographic area. Given the conditions at the intersections of the grid points, computers solve complex differential equations to fit the model to the current weather conditions, and then advance time to predict future conditions.

Clearly, as the grid distances become smaller, the forecast becomes more accurate, but the computing power needed increases dramatically. One recent model, which had to wait for computing power to catch up before it could be deployed, is the High-Resolution

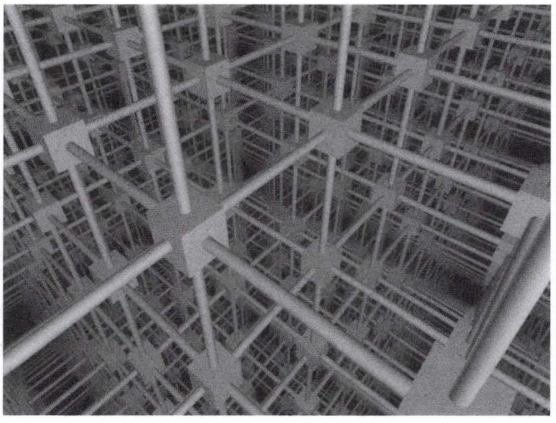


Figure 5.1: 3D Grid Points

Rapid Refresh (HRRR) model. This model covers the whole of the contiguous USA and Canada up to the middle of Hudson Bay with grid points every 3 km horizontally and 51 levels vertically between sea level and 150mb. The calculations are run hourly (hence "rapid refresh") and incorporate not only currently reported conditions, but also factors such as smoke from forest fires and the intensity of the sun's radiation; in 2017 it even took into account the eclipse of the sun that crossed North America.

The HRRR and other models, such as the North American Mesoscale (NAM) and the *Rapid Refresh* (RAP), are made available to meteorologists and forecasts are derived directly from them, for example, the ASEP products from Nav Canada and the skew-T diagrams explained in section 5.4.4 below, or are interpreted by human meteorologists to produce GFAs, TAFs, SIGMETs, FDs, FBs and other forecasts.

Raw data from these models are also generally available on the Internet: a simple search will find them.

Statistical Models

Statistical models accept dynamical models as part of their input, but they also integrate data from other sources, including history. A commonly-used statistical model in North America is the National Oceanic and Atmospheric Administration (NOAA) *Model Output Statistics* system (MOS).

Figure 5.2 illustrates the type of report from MOS that is available on the NOAA website. It can be seen that the report is for Syracuse, NY, USA (KSYR) and that it was produced at a particular date (note: month before day) and time. Forecasts of various lengths are available—the one shown here is for three days. The identifiers of the rows are somewhat cryptic, but the NOAA website has the full expansion of each.

The X/N row provides the estimated daily maximum

```
KSYR   GFS MOS GUIDANCE    3/23/2018  0000 UTC
DT /MAR  23           /MAR  24           /MAR  25           /
HR   06 09 12 15 18 21 00 03 06 09 12 15 18 21 00 03 06 09 12 18 00
X/N                 38          25          33          21    39
TMP  30 29 28 33 36 35 32 30 29 28 26 29 31 30 24 22 24 24 25 36 33
DPT  27 26 25 27 26 25 25 24 24 22 21 22 21 20 18 16 16 17 18 21 19
CLD  OV OV OV OV OV OV OV OV OV OV OV OV OV BK SC OV BK BK BK FW CL
WDR  27 27 27 29 30 30 29 30 30 31 32 33 32 32 33 34 35 34 01 02 36
WSP  10 08 09 09 10 11 06 06 06 06 07 07 09 10 06 06 06 06 06 07 04
P06        25    49    32    13     7    22    18     8     3  2  0
P12                    49          18          24           8     2
Q06         0     1     0     0     0     0     0     0     0  0  0
Q12                    1           0           0           0     0
T06      0/ 0  1/ 0  0/ 0  0/ 0  1/ 0  1/ 0  1/ 0  1/ 0  1/ 0  1/ 0
T12         1/ 0        0/ 0        1/ 0        1/ 0        1/ 0
POZ   2  2  3  3  0  0  0  0  0  0  1  1  0  1  1  1  1  0  0  0  0
POS  95 99 97 97 99 99 99100100100 99100100 99 99 99 99100100 84 84
TYP   S  S  S  S  S  S  S  S  S  S  S  S  S  S  S  S  S  S  S  S  S
SNW                                 1                       0
CIG   6  5  5  5  5  6  6  6  6  6  6  6  6  6  6  6  8  8  8  8  8
VIS   7  7  7  4  3  5  7  7  7  7  7  7  7  7  7  7  7  7  7  7  7
OBV   N  N  N BR BR  N  N  N  N  N  N  N  N  N  N  N  N  N  N  N  N
```

Figure 5.2: Sample MOS Output

and minimum temperatures two metres above the ground and TMP and DPT provide the anticipated temperature and dew point (all in degrees Fahrenheit; see page 49 for the method of conversion to Celsius).

The CLD row is self-explanatory, giving the expected cloud cover and this can be combined with the CIG row which gives the height of the first broken or overcast layer (i.e., the ceiling). In figure 5.2 the 6 indicates between 3,100 and 6,500 ft, 5 indicates between 2,000 and 3,000 ft, and 8 indicates above 12,000 ft.

What makes a statistical model different from a dynamical one is that it also provides probabilities of phenomena occurring. The POS row, for example, gives the estimated probability of snow falling during the 12 hours before the given time.

Completing the Forecast

Although some forecasts (e.g., the ASEP products) are taken directly from the models, for TAFs and other forecasts, human forecasters take the output from models and fine-tune them using local knowledge. This can be seen in the *Aviation Forecast Discussions* on the USA *Aviation Weather Center* website. This discussion contains comments such as: *"No significant change to previous forecast, though did nudge back timing an hour. Latest suite of forecast soundings also indicating a faster transition over to snow for the Chicago terminals. Cannot completely rule out a brief window of sleet or pellets, but low confidence and expected short duration precludes further mention in the TAF."*

5.3 Aviation Weather Reports

It is important when reading weather products to differentiate between those products that *report* actual conditions as measured by a human operator or automated system, and those products that *anticipate* what will happen to the weather in the future. This section covers reports of actual conditions while section 5.4 covers forecasts.

5.3.1 Decoding Weather Reports

New pilots are often surprised by the terseness and strange encoding of weather reports and forecasts. People born since the Telex service became obsolete may not remember that Telex machines could only carry upper-case letters, digits and a few punctuation marks. Telex transmissions operated at 8 characters per second (80 Baud) and therefore weather reports needed to be terse and expressed solely in upper-case letters. In today's world of multi-megabit per second connexions to the Internet, the continued use of the Telex format for weather reports and forecasts is being assessed for upgrading. The move, already undertaken, from a textual to a graphical area forecast (GFA) was a step towards modernising the decoding of weather reports.

"Decoding" is Transport Canada's term; for some reports and forecasts "decrypting" might be more appropriate. Various computer programs exist to decode reports and forecasts into formats more readable by human beings, but the format of the reports and forecasts is not simple and is not always consistently applied.

5.3.2 Aviation Routine Weather Report

Human Observation

A routine weather report is known world-wide as a METAR, a term believed to derive from the French phrase MÉTéorologique Aviation Régulière.

A METAR is not a forecast—it is a report of the weather recorded at a particular time at a particular location. Typically METARs are issued hourly (on the UTC hour) or when some significant change in the weather (e.g., a thunderstorm) occurs.

Exam Hint 9 *Note that METARs are issued on the UTC (i.e., Zulu) hour. In Newfoundland, where the standard time zone time is 3 hours 30 minutes behind UTC, the METARs are issued hourly but on the half hour in local time.*

The structure of a METAR is illustrated in figure 5.3 and consists of the following fields:

The Report Type consisting of the word "METAR" to indicate that it is a standard, on the hour, report or "SPECI" to indicate that it is a special report issued between two METARs.

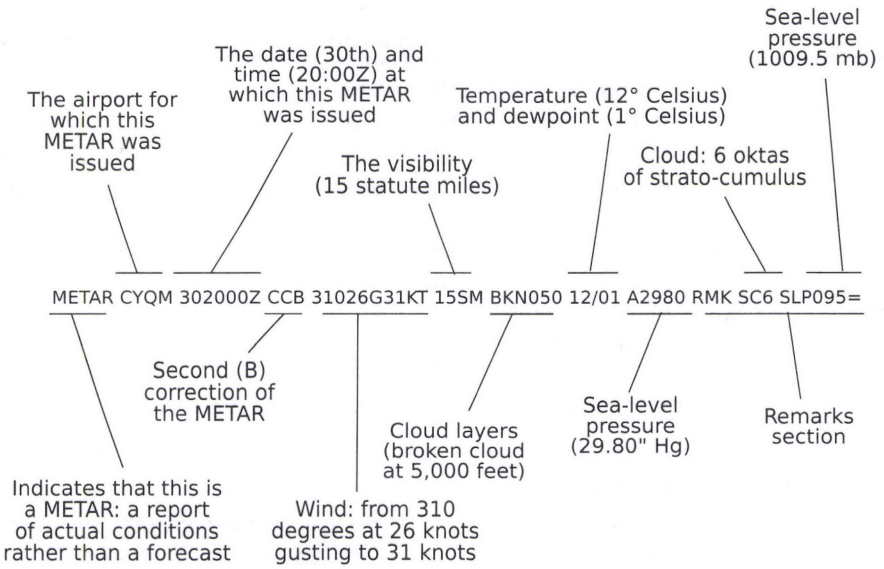


Figure 5.3: A Sample METAR

The **ICAO identifier** of the aerodrome where the observation was made.

The **date and time** at which the observation was made formatted as `DDHHMMZ` where `DD` is the day of the month, `HH` is the (Zulu) hour of the day and `MM` is the minute of the hour.

Possibly the term **CCA** to indicate that this is not a new METAR, rather it is a correction to a previous METAR. If such a correction needs to be corrected, then this field would be CCB, and so on.

The **wind conditions.** The first three digits are the direction from which the wind is coming in degrees true (rather than magnetic), and the remaining characters are its strength in knots. If the wind is gusting, then the average wind speed is given, followed by the letter *G* and the gust speed.

The **visibility** in statute miles.

The **runway visibility range** if the general visibility is less than a mile or the runway visibility range is 6,000 ft or less.

Any **special phenomena** such as rain, snow, thunderstorms, volcanic ash or sand storms. A list of these is given in figure 5.4. These conditions may be prefixed by a minus sign to mean "light", a plus sign to mean "heavy" or the letters VC to mean "in the vicinity". No prefix means "moderate".

The **cloud layers** indicating whether they are:

- SKC—Sky clear: less than $\frac{1}{8}$ of the sky covered
- FEW—A few clouds: $\frac{1}{8}$ to $\frac{2}{8}$ of the sky covered
- SCT—Scattered clouds: $\frac{3}{8}$ to $\frac{4}{8}$ of the sky covered
- BKN—Broken clouds: $\frac{5}{8}$ to $\frac{7}{8}$ of the sky covered
- OVC—Overcast: sky completely covered

The cloud height is given in hundreds of feet above ground level.

Exam Hint 10 *Note that cloud height in a METAR is given above ground level whereas forecast cloud height in a graphical area forecast (GFA) is given above sea level. This makes sense because a GFA covers a large area where the ground level is not constant, whereas the METAR is for one particular aerodrome where the ground level is known.* *See also hint 11 on page 103.*

The **temperature and dew point** in degrees Celsius. Negative temperatures are indicated by the letter M: thus M20 means −20°C.

The **sea level altimeter setting** in hundredths of an inch of mercury. Thus A2992 means 29.92″ Hg.

Any **recent significant weather** such as freezing rain, dust storms, volcanic ash or thunderstorms.

Any **wind shear** that has been reported at low altitude.

Description		Precipitation		Visibility		Miscellaneous	
MI	Shallow	DZ	Drizzle	BR	Mist	SQ	Squalls
BC	Patches	RA	Rain	FG	Fog	FC	Funnel Cloud
DR	Drifting	SN	Snow	FU	Smoke	DS	Dust Storm
BL	Blowing	SG	Snow Grains	VA	Volcanic Ash	PO	Dust/Sand Whirls
SH	Shower	IC	Ice Crystals	DU	Dust	+FC	Tornado or Waterspout
TS	Thunderstorm	PL	Ice Pellets	SA	Sand	SS	Sandstorm
FZ	Freezing	GR	Hail	HZ	Haze		
PR	Partial	GS	Snow Pellets				
		UP	Unknown Precip				

Figure 5.4: Common Conditions Reported in METARs

Remarks describing the types of clouds, the sea level pressure in hectopascals and any additional notes (such as the observer being unable to reach the recording equipment because of the presence of a bear—something that has actually appeared in a METAR). The types of cloud are given as an abbreviation (e.g., SC for stratocumulus) followed by a single digit indicating how many eighths ("oktas") of the visible sky are covered by that cloud layer.

Exercise 27 *How would you interpret the following conditions in a METAR?*

```
VCSHRAGR

MIFG
```

Possible answers to the examples are given at the end of the chapter, starting on page 111.

Exercise 28 *Given the following two METARs, explain why two METARs were issued for the same date and time.*

```
METAR CYND 030100Z CCA 01003KT 360V070 15SM
       MIFG FEW041 SCT140 22/22 A3005
METAR CYND 030100Z 01003KT 360V070 15SM
       MIFG FEW140 22/22 A3005
```

Exercise 29 *Interpret the following METAR:*

```
METAR CYYQ 281600Z 33015G20KT 15SM DRSN SKC
M28/M33 A3045 RMK SLP317
```

Exercise 30 *Consider the following METARs for Ottawa International airport.*

```
METAR CYOW 282100Z 35003KT 20SM SKC
       M12/M21 A3040 RMK SLP306=
METAR CYOW 282000Z 33002KT 20SM SKC
       M12/M22 A3042 RMK SLP313=
METAR CYOW 281900Z 32004KT 20SM SKC
       M14/M23 A3045 RMK SLP324=
```

Comment on the changes in the atmospheric pressure and wind direction.

Machine Observation

The report from an AWOS or LWIS looks very similar to a METAR derived from a human observation. The differences are:

- If the report is derived from an LWIS, then the word METAR is replaced by LWIS. If the report is derived from an AWOS or an LWIS then the word AUTO is included after the date/time group.
- The term CLR is used rather than SKC to indicate that the sky is clear (up to the height that the device can detect).
- The number of fields is limited to those that the device can measure.

5.3.3 Weather Radar

Environment Canada has a network of 31 weather radar sites across Canada, each with a range of 250 km, and the National Weather Service in the USA has a further 30 radars located sufficiently close to the Canadian border to provide useful information for pilots flying within Canadian airspace. The radar sites are chosen so

that their areas of coverage overlap and composite views can be drawn, combining the views from several radars.

Weather radars transmit bursts of radio waves and then measure the strength, delay and phase shift of any echoes received back. If there is no precipitation within range then the only echoes will be those from mountains and other ground features. As these will always be the same, they can be filtered out, leaving a clear display. If heavy precipitation is within range, then the radio waves reflect off the water droplets and are received back at the radar site. The time taken for the echo to be received allows the distance to the precipitation to be calculated; the strength of the echo allows an assessment to be made as to whether the precipitation is heavy rain, light or moderate rain, or snow.

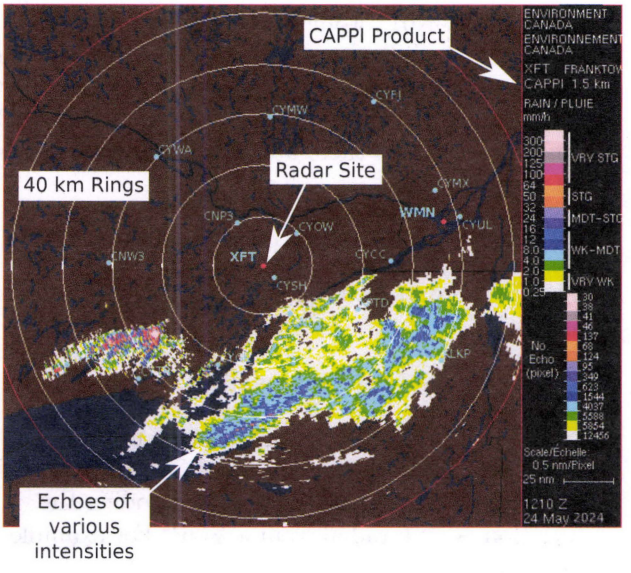


Figure 5.5: CAPPI Weather Radar Image

Once the echoes have been received and processed they can be displayed both as static images and as animations that show how the precipitation is forming and moving. The readings are also available in textual form if you wish to do your own analysis.

Environment Canada provides two graphical weather radar products:

1. The *Constant Altitude Plan Position Indicator* (CAPPI) image. This provides a view of the precipitation at 1.5 km (about 5,000 ft) above the height of the radar transmitter. Figure 5.5 gives an example of this type of view. The intensity scale on the right of figure 5.5 is a measure (in dBZ)[2] of the amount of transmitted energy reflected by the precipitation. In winter this is correlated to snowfall rate in centimetres per hour, and in summer to rainfall rate in millimetres per hour.

2. The *Echo Tops* image. This estimates the height of the top of the precipitation (actually the maximum height from which reflections greater than 18 dBZ are detected). Figure 5.6 provides an example of the echo tops display. In this case the scale to the right of the picture indicates the estimated height above sea level of the top of the precipitation. For example, in figure 5.6 the dark blue areas indicate tops between 20,000 and 23,000 ft above sea level. From the point of view of a pilot, the echo tops view can help distinguish between heavy rain from a nimbostratus cloud topped at 13,000 ft and heavy rain from a thunderstorm topped at 40,000 ft—a useful distinction!

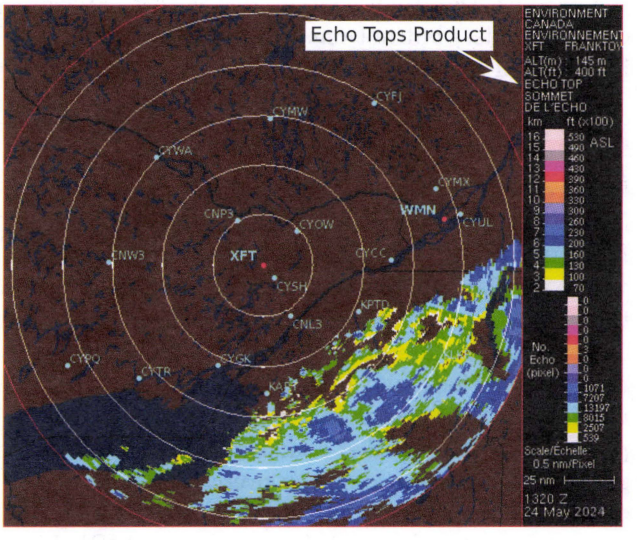


Figure 5.6: Echo Tops Weather Radar Image

Interpreting the weather radar image is not easy and Environment Canada provides a webpage describing common interpretation errors:

Blocking Beam. This occurs when a hill or mountain blocks the radar beam and, when the echoes from the mountain are filtered out, leaves what appears to be an area without precipitation. In fact the mountain might be masking an area of intense precipitation. This is very common in the Rockies and Newfoundland.

Beam Attenuation. In this situation, a strong area of precipitation close to the radar site reflects much of the energy of the radar beam and another area of heavy precipitation in the same direction, but further away, is shown lighter than it really is.

[2]Decibels Z. This is a logarithmic measure of both the number of droplets in a cubic metre of air and the size of those droplets.

Overshooting Beam. The further an area of precipitation is from the radar transmitter, the higher the radar beam is from the ground. Heavy precipitation arising from phenomena close to the ground (e.g., snow-squalls from a lake) may therefore be missed or be displayed as less intense than they really are.

Anomalous Propagation. When there is a strong temperature inversion, the radar beams can be "bent" by refraction and sometimes hit the ground. This gives a strong echo that is interpreted as precipitation even when no precipitation is falling. This occurs most often in the early morning and generally disappears by the middle of the day.

As described on page 223, these weather radar pictures can be uploaded to the cockpit and displayed on a GPS-based moving map. This provides a wider view of the local weather than a sferics device (e.g., Stormscope or Strikefinder) but not one as up-to-the-minute. For information about sferics devices see page 224.

5.3.4 Pilot Reports

Pilot reports are also reports of weather conditions. NAV CANADA encourages pilots to provide Pilot Reports (PIREPs) of weather conditions when the actual weather conditions encountered differ, either for the better or worse, from those forecast. In many areas of Canada there are large distances between weather reporting stations, and PIREPs are therefore a really useful source of information to meteorologists. Also, pilots can detect weather conditions invisible from the ground: cloud layers above an overcast, estimates of cloud tops, occurrence of icing, etc.

The format to be used when making a PIREP is given on the back of the Canada Flight Supplement; this formal format should not discourage you from providing informal PIREPs because Flight Service Station representatives are able to interpret and encode informal descriptions as well.

Exercise 31 *You are flying a Piper Cherokee at 6,000 ft ASL over an undercast layer of stratus cloud which appears to be about 1,000 ft below you. At 13:15Z you are 34 nautical miles east of the Mirabel VOR (YMX) on the 072 (V318) radial. The outside air temperature is* $10°C$ *and, using the feature on your GPS, you estimate that the wind is coming from* $320°M$ *at 24 knots. You are not encountering any turbulence. Since this weather is significantly better than that forecast, you decide to make a PIREP to Québec Radio. How would you make this report?*

Through its website and briefings, NAV CANADA provides pilots with access to PIREPs both as plain text and in the "standard" form. As with weather forecasts and reports, the standard form is cryptic and needs interpreting. Consider the following PIREP in standard form:

```
UACN10 CYYY 241436
UL
UA /OV CYFE /TM 1436 /FLUNKN
/TP C310 /RM -SHRA OVR YFE
```

This PIREP can be interpreted as follows (see figure 5.7 for a full list of labels):

The first word is probably the most cryptic of all: **"UACN10"** labels this as a non-urgent PIREP while "UACN01" would have meant that it was urgent. It is difficult to understand why this could not be made clearer (perhaps using "URGENT" to mean urgent!). Note that only the two numbers 01 and 10 are used—there are no intermediate degrees of urgency.

CYYY refers to the issuing office (Mont-Joli).

241436 is the date/time group: the 24th of the month at 14:36Z.

UL indicates the Flight Information Region: Montréal.

UA /OV CYFE provides the location of the reporting aircraft—overhead the CYFE (Forestville) aerodrome. A common means of encoding the location is by a radial from a VOR. For example

```
/OV YXU 090010
```

would mean due east (090) of the YXU (London) VOR at a distance of 10 nautical miles.

/TM gives the time of the observation. Note that this might be earlier than the issuing time.

/FLUNKN indicates the altitude of the aircraft: in this case at an unknown flight level (the pilot has not given an altitude because it is irrelevant for the PIREP). Other common abbreviations are /FLDURD to mean "during descent" and /FLDURC to mean "during climb".

/TP C310 indicates the type of aircraft: a Cessna 310. This information can obviously be useful when you are interpreting a turbulence report; see section 4.13.5 on page 86.

/RM prefaces the remarks. In this case the remark is that light rain showers were encountered over Forestville.

Forestville lies in a fairly remote area on the north shore of the St Lawrence river and a PIREP of this nature could provide useful information to an arriving pilot—perhaps the forecast for the area was calling for heavy rain or clear skies.

Label	Meaning	Label	Meaning
/OV	Position	/TM	Time
/FL	Altitude	/TP	Type of aircraft
/SK	Clouds	/WX	Weather
/TA	Air Temperature	/WV	Wind
/TB	Turbulence	/IC	Icing
/RM	Remarks		

Figure 5.7: Labels Used in a PIREP

Exercise 32 *How would the PIREP you made in exercise 31 appear as a PIREP report?*

5.4 Aviation Forecasts

5.4.1 Graphical Area Forecasts (GFA)

Graphical Area Forecasts (GFAs)[3] are forecasts of the weather over reasonably large areas. GFAs are issued for the following regions: Arctic, Yukon and Northwest Territories, Nunavut, Pacific, Prairies, Ontario-Québec and Atlantic.

A complete set of GFAs consists of 6 charts: a pair for the beginning of the forecasting period, another pair valid 6 hours after the beginning of the forecasting period and a third pair valid 6 hours after that. Each pair consists of one chart showing forecast clouds and weather patterns and another showing the forecast icing, turbulence and freezing level. The final clouds and weather chart also contains an IFR outlook for the following 12 hours.

GFAs are issued at about 23:30Z, 05:30Z, 11:30Z and 17:30Z and are valid at 00:00Z, 06:00Z, 12:00Z and 18:00Z.

Figure 5.8 gives an example of one of the six charts that comprise a GFA—the clouds and weather forecast for the Ontario-Québec region. Annotations in red and labels Ⓜ, Ⓝ, Ⓞ and Ⓟ have been added for ease of reference—they do not appear on the original GFA. Figure 5.9 shows the corresponding freezing level GFA.

The following points can be noted in the example:

- Item Ⓜ is an area of high pressure. In this case the high pressure is expected to move south-south eastwards at 30 knots and the pressure at its centre is 1017 hectopascals. The isobars around the areas of low and high pressure are shown at 4 hectopascal intervals.
- Item Ⓝ shows a wind arrow. These are described on page 109 and the one shown in the diagram indicates a wind speed between 30 and 34 knots (three full-size barbs at the tail) from the north west.
- Item Ⓞ shows a cold front lying almost north/south from the low pressure system over Hudson's Bay. The front is moving eastwards at 20 knots.
- Item Ⓟ shows how an area with similar weather is represented: it is bordered by a coloured line. Unbroken green lines around the area indicate areas of continuous non-freezing precipitation; red lines indicate areas of continuous freezing precipitation. Dashed green lines would indicate areas of intermittent precipitation and dashed orange lines would indicate areas of obscuring phenomena other than precipitation (e.g. haze). However, in this case the line is continuous and green and the associated text reads

  ```
  OVC LYRS 220/25
  2-6SM -RA -DZ BR
  XTNSV CIGS 3-8 AGL
  SCT ACC 240
  1SM SHRA BR
  ```

  Using figure 5.4 and some language skills, this can be translated to read: "Overcast layers from 2,500 ft ASL to 22,000 ft ASL. Visibility 2 to 6 statute miles in light rain, light drizzle and mist. Extensive ceilings at 300 ft to 800 ft AGL. Scattered altocumulus castellanus at 24,000 ft ASL with visibility 1 statute mile in rain showers and mist."

  Note that, unlike terminal area forecasts, cloud heights are given above sea level rather than above ground level. This is because the GFA covers such a large area that there is no consistent ground height.

If the forecasted weather changes between the issue times of GFAs then a new GFA is issued to update the forecast. Before 14th November 2013, an AIRMET (see section 5.4.6) or SIGMET (see section 5.4.5) would have been issued to correct a GFA.

5.4.2 Terminal Area Forecasts (TAF)

As its name suggests, a terminal area forecast is a forecast for a small area around an airport—the area

[3] You may wonder why the acronym is not GAF. Area forecasts are termed FAs internationally and when Canada moved to Graphical Area Forecasts some years ago, no attempt was made to change the acronym.

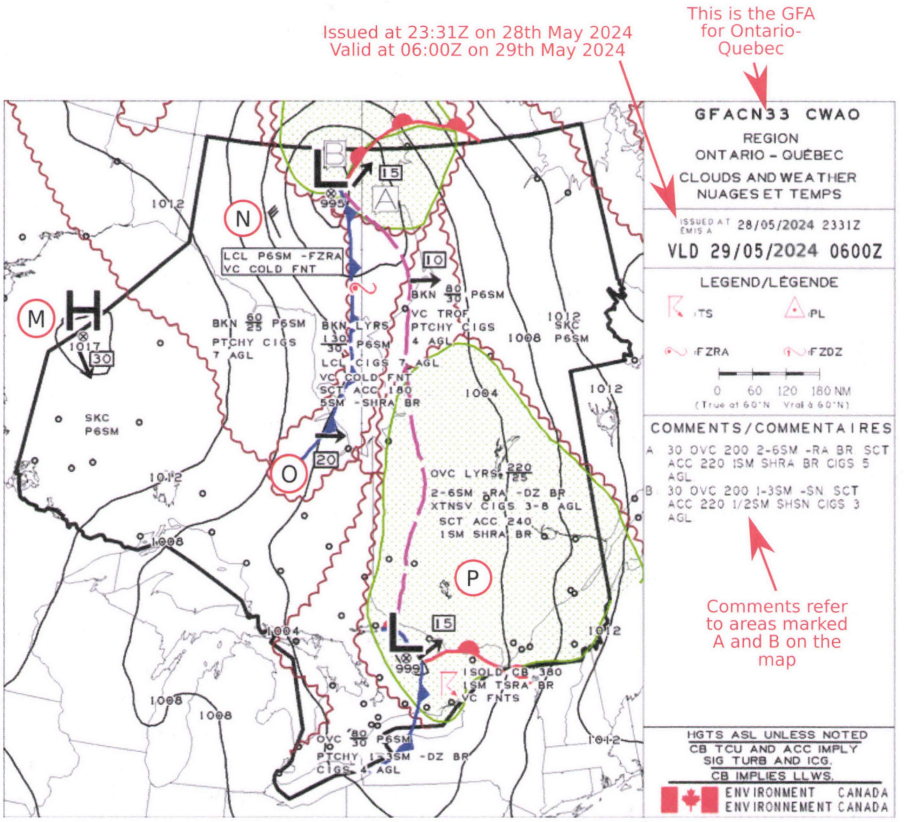


Figure 5.8: An Annotated Weather GFA

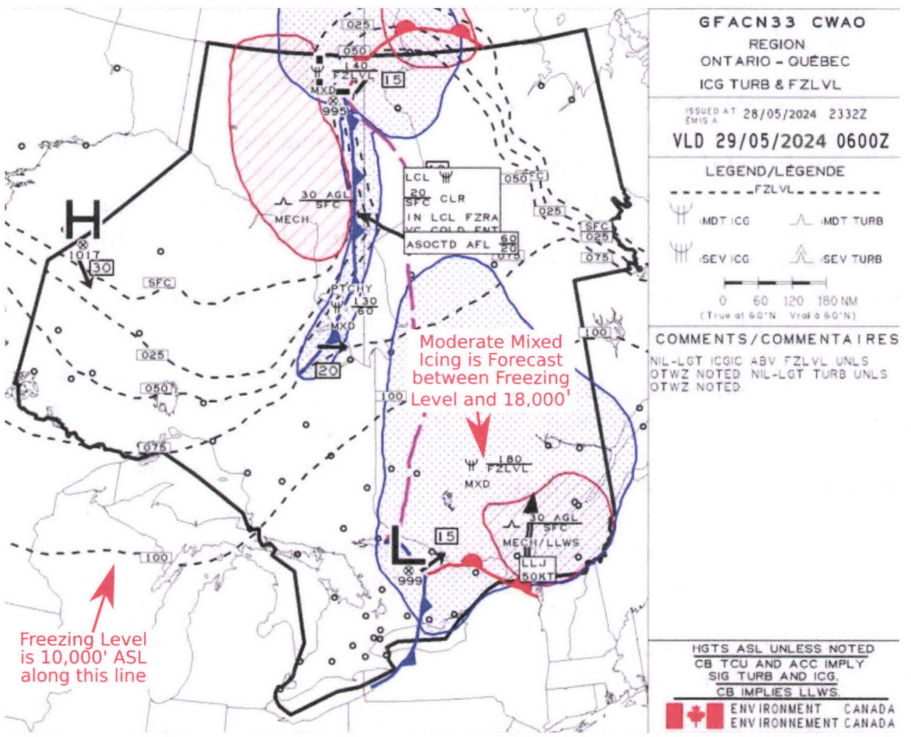


Figure 5.9: An Annotated Freezing Level GFA

within five nautical miles of the centre of the runway complex. This is important: if you are flying from one airport to another 150 miles away, and you brief yourself by reading only the TAFs for the two airports, then you will be familiar with the forecast weather for only the first and last five miles of the 150 mile trip.

TAFs are issued ten or twenty minutes before the time period they cover but are actually immediately valid, cancelling any earlier TAF. Thus a TAF covering the period from 11:00Z to 23:00Z issued at 10:40Z is valid from 10:40Z. This means that forecasters do not have to issue corrections to TAFs that are about to expire—issuing a new TAF is adequate.

Figure 5.10 gives an annotated example of a TAF: many of the terms are the same as those in a METAR (see figure 5.4) but, as this is a forecast of expected conditions rather than a report of actual ones, there are temporal qualifiers: "we anticipate the weather will be X but it will later become Y and there will be temporary periods of Z". The codes for these types of temporal information are as follows:

BCMG ddhh/ddhh. This prefixes an anticipated change in the weather that is forecast to occur between the first date/hour group and the second. Thus **BCMG 1213/1215** means that the weather is expected to transition between 13:00Z and 15:00Z on the 12th of the month.

FMddhhmm. This prefixes new weather that is forecast to exist from the time given. Thus **FM231230** means that the new weather is expected from 12:30Z on the 23rd of the month.

TEMPO ddhh/ddhh. This prefixes weather that is expected to occur for temporary periods (less than one hour and, if expected to recur, not covering more than half of the period) between the two times given. Thus **TEMPO 1413/1418** prefixes weather expected to occur temporarily between 13:00Z and 18:00Z on the 14th of the month.

In a TAF:

- All wind directions are given in degrees true.
- Cloud heights are above ground (rather than sea) level.
- If the wind speed is forecast to be 3 knots or less the direction is not given: it is replaced by VRB—"variable" (e.g., VRB03KT).
- The term NSW means "No Significant Weather".
- If the sky is forecast to be obscured (by fog, etc.) then a vertical visibility is given in hundreds of feet prefixed with VV. Thus **VV005** means that the vertical visibility is expected to be 500 ft.

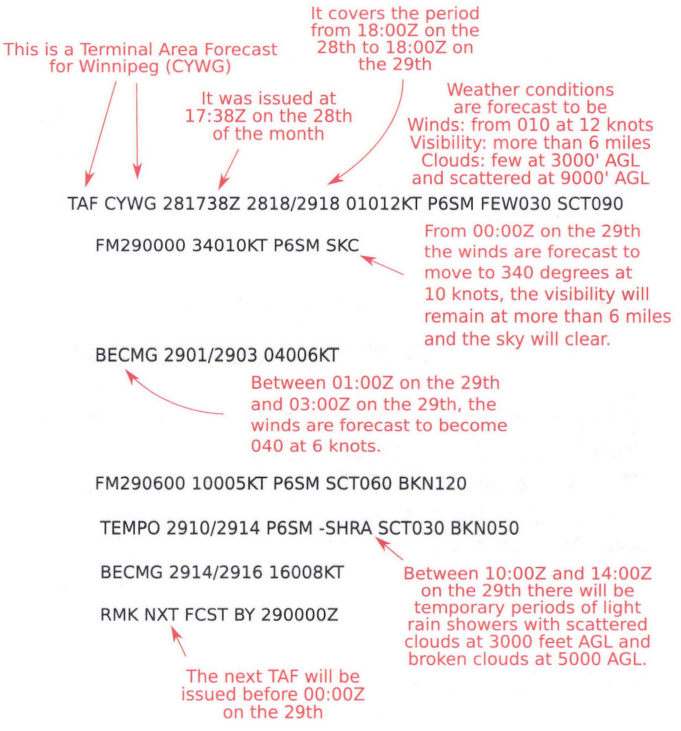


Figure 5.10: An Annotated TAF

- The term **PROB30** or **PROB40** is used as a prefix to a weather description to indicate that there is a 30% or 40% probability (these are the only two values allowed—a forecaster cannot, for example, say that there is a 20% probability) of the phenomenon occurring. The PROB term is only used for phenomena of importance to pilots: thunderstorms, freezing precipitation, low level wind shear (below 1,500 ft AGL) and decreases in ceiling or visibility important to aircraft operations.
- Apart from the time of the next forecast as shown in figure 5.10, the other phrase that often occurs in the remarks section is "FCST BASED ON AUTO OBS" to indicate that the forecast has been based on readings from an automated system (AWOS or LWIS) rather than a human observer.

Exam Hint 11 *You may find it difficult to remember when cloud heights are given AGL and when ASL. It is actually logical. METARs and TAFs relate to small areas where the height of the ground can be defined. The heights in those are therefore AGL. GFAs and surface analysis charts cover a much larger area and there is no clear definition of the height of the ground. The cloud heights therefore have to be given ASL.*

Sometimes TAFs have to be updated when conditions change unexpectedly. In this case an update is issued which supersedes the previous TAF without extending its validity period (e.g., if the previous TAF was valid from 11:00Z on one day to 11:00Z on the next, and an update is issued at 18:00Z, then it will be valid from 18:00Z until 11:00Z).

Exercise 33 *Decode the following TAF:*

```
TAF AMD CYEG 151912Z 1519/1618 27015G35KT
3SM -TSRA SCT008 OVC015CB
TEMPO 1520/1523 25035G45KT 1SM TSRAGS OVC008CB
PROB30 1520/1523 1/2SM +TSRAGR
FM160000Z 33015G25KT P6SM SKC
BECMG 1609/1610 33005KT
RMK NXT FCST BY 152130Z=
```

5.4.3 Upper Winds & Temperature Forecasts (FD/FB)

The upper winds are forecast twice daily for 140 sites across Canada at pressure altitudes of 3,000 (unless the terrain elevation is above 1,500 ft), 6,000, 9,000, 12,000, 18,000, 24,000, 30,000, 34,000, 39,000, 45,000 and 53,000 ft ASL. Temperatures are forecast for all of these altitudes except for 3,000 ft. The forecasts are based on data available at 00:00Z and 12:00Z and forecasts are created for 6, 12 and 24 hours ahead. Thus the forecasts based on 12:00Z data will be for 18:00Z, 00:00Z and 12:00Z the following day.

The forecasts are available in tabular (FD) or digital (FB) form. The digital format is specified in Environment Canada's document *MANAIR—Manual of Standards and Procedures for Aviation Weather Forecasts*, unfortunately in informal text rather than a computer-readable form such as XSD.

The wind speeds and directions in the FDs are coded in a rather Byzantine manner:

- If the wind is forecast to be less than 5 knots then it is encoded as 9900±tt where ±tt is the forecast temperature. Thus a wind of 4 knots with the temperature of −10°C would be encoded as 9900-10.
- If the wind is forecast to be between 6 and 99 knots inclusive then it is encoded as ddss±tt where dd is the direction with the least significant digit omitted, ss is the speed in knots and ±tt is the temperature in degrees Celsius. Thus 3210+07 means the wind is forecast to be from between 315° True and 324° True at ten knots and the temperature is forecast to be +7°C.
- If the wind is forecast to be between 100 and 199 knots inclusive, then 100 knots are subtracted from the speed of the wind and 500° is added to its direction! Thus a wind of 125 knots from 200°T would be encoded as 7025. Meeting 7025, the pilot would break it into a wind "direction" of 700 and a speed of 25 knots. Realising that the direction was invalid, 500 would be subtracted (to give 200°) and 100 would be added to the speed (to get 125 knots).
- If the wind is forecast to be above 199 knots, then it is encoded exactly as though it were 199 knots. For example, a wind from 90°T at 210 knots would be encoded as 5999.

The encoding of the temperature is simpler except that the ± sign is dropped above 24,000 ft ASL where temperatures are all assumed to be negative.

Exercise 34 *Consider the FDs given in figure 5.11. What wind and temperature conditions are forecast for 34,000 ASL at St Anthony, Newfoundland at 04:00Z on the 26th of the month?*

5.4.4 Skew-T Charts

Skew-T charts are probably one of the most useful tools for understanding the state of the atmosphere. In the past they have been created from reports returned from weather balloons or sensors fitted into commercial aircraft. However, they are now available from the NOAA website as forecasts, built from the models described in section 5.2.2. These are not Canadian products and will therefore not appear on the Transport Canada written examination. However, they are products that provide a pilot with useful, if not essential, information for flight planning.

There is a lot of information on a skew-T that can be interpreted very quickly: almost at a glance. However it should be borne in mind that this represents the output of a model, and is a model of the atmosphere at one point.

At first glance, a Skew-T charts can appear intimidating. After a simple introduction, a pilot can read cloud layers, atmospheric stability, winds aloft and other useful information from them at a glance. Figure 5.12 illustrates the blank skew-T paper: the lines that are common to all skew-T charts.

Temperature is represented along the bottom of the chart (from −40°C to +40°C in figure 5.12) but the red line for a particular temperature does not climb vertically; rather it moves towards the top

STN YAY—ST. ANTHONY. NFLD	for use	24000	30000	34000	39000	45000	53000
FDCN01 KWBC DATA BASED ON 251200Z VALID 251800Z	1700-2100Z	2551-38	256646	255149	243946	252947	251850
FDCN02 KWBC DATA BASED ON 251200Z VALID 260000Z	2100-0600Z	2435-41	235847	244747	252944	252046	261649
FDCN03 KWBC DATA BASED ON 251200Z VALID 261200Z	0600-1700Z	3218-42	322050	302045	291842	271245	271248

Figure 5.11: Sample FD—see Exercise 34

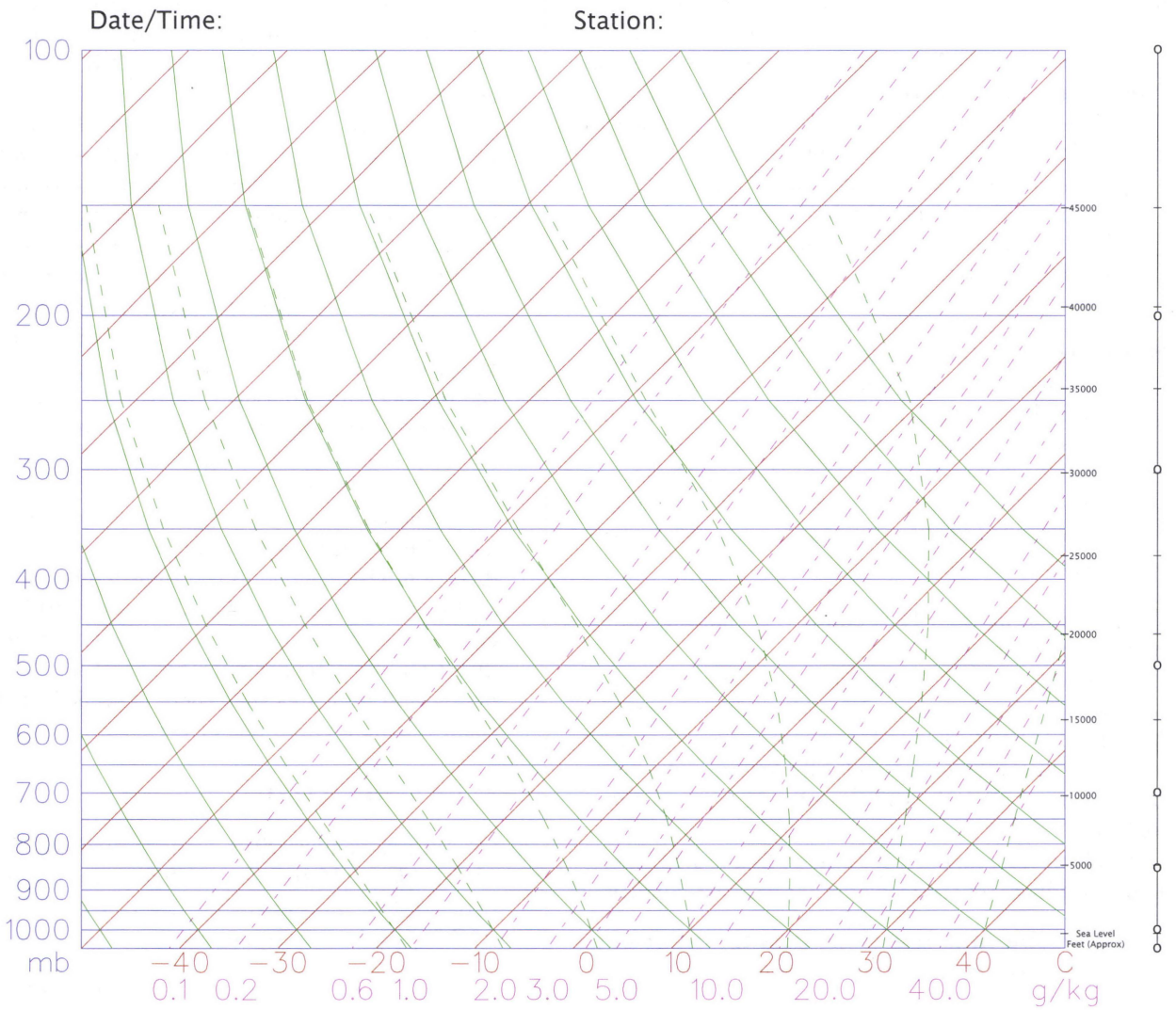


Figure 5.12: Skew-T Chart Template

right-hand corner of the chart—hence the name "Skew T": "skewed temperature".

The vertical scale is **altitude** measured in millibars up the left side and feet ASL up the right. The equivalence between the millibars and the height ASL is for a standard atmosphere: it would not represent the actual conditions on the day of the forecast. The 700mb level is at approximately 10,000 ft ASL and the 500mb level is at about 18,000 ft ASL. The millibar scale is logarithmic rather than linear because, as can be seen from the almost regular spacing of the feet ASL on the right, atmospheric pressure drops roughly logarithmically with height. For this reason, the chart is sometimes called a "Skew-T, Log-P" chart.

Of critical importance to the pilot, particularly in the summer when thunderstorms are more likely, is a measure of the stability of the atmosphere. The **dry adiabatic lapse rate** (a fixed quantity—see section 4.9.4 on page 76) is marked on the chart by the coloured, curved lines drawn from the bottom upwards and to the left (adiabats). Thus, taking the adiabat that meets the bottom of the chart at +3°C, we can read that, by 10,000 ft ASL (≈700mb), the temperature has reduced to −26°C: a drop of about 3°C per 1000 ft as expected.

The **saturated adiabatic lapse rate** is also marked on the chart: as the coloured lines curving initially to the right from the bottom of the chart, and then towards the top, left-hand corner. Taking the saturated adiabat that starts at the bottom at about +11°C, we can see that by 10,000 ft ASL, it has dropped to about −7°C: a drop of just under 2 Cdeg per 1000 ft.

The chart in figure 5.12 is empty—it contains no actual information.

In contrast, figure 5.13 contains an example of an actual skew-T chart generated for Mont Joli airport (CYYY). This has been produced from a model and, as can be seen in the title, it is actually for a point about 7 miles south of CYYY—the closest grid point in the model to CYYY.

As well as the standard lines from figure 5.12, there are now two lines representing actual forecast conditions:

1. **The strong blue line** rising from the centre of the bottom of the chart is the dew point.
2. **The strong red line** to the right of the dew point line is the temperature.

From these, we can deduce a lot about the forecast atmospheric conditions above CYYY:

- The temperature (strong red line) at the surface at CYYY (142 ft ASL) is −1°C and the dew point (strong blue line) is very slightly less than that. This aligns with the METAR taken for the same date and time: M01/M01.
- The temperature and dew point move apart and then meet again at about 848mb: 5,026 ft ASL or 4,900 feet AGL. This also aligns with the METAR: the first layer of cloud is reported as OVC050.

What the METAR cannot tell us is how thick the overcast cloud layer is, and whether there are additional layers above it. The Skew-T indicates that above the 817mb level (about 6,000 ft ASL), the temperature and dew point move far apart and remain apart to the maximum height on the chart—there are therefore no cloud layers above the fairly thin layer based at 5,000 ft ASL. This is useful information, particularly for a pilot planning to fly over CYYY on a VFR OTT flight plan (see page 322).

A measure of the stability of the atmosphere is also important to a pilot. The thick, red temperature line can immediately be compared with the adiabatic lines to see whether the atmosphere is unstable (temperature line moving more left-wards than the adiabats) or stable. In the case of figure 5.13, the temperature line is more vertical than the adiabatic lines, indicating stability.

For pilots flying high-altitude aircraft, the height of the tropopause is also a useful value. At the tropopause, the temperature no longer drops with height—the thick, red temperature line will start to move in parallel with the thin temperature lines. In figure 5.13 this starts to occur at 35,000 ft ASL.

While not strictly part of the Skew-T diagram, figure 5.13 also contains other information—wind strength and direction with height up the right-hand side and a hodograph (see section 4.6.12 on page 69) in the top-left corner. Again, the surface wind shown aligns in direction and strength with the METAR. The hodograph indicates that there is unlikely to be wind shear during a climb out of CYYY.

5.4.5 SIGMETs

On 14th November 2013, Canada changed the purpose of *Significant Meteorological Information* reports (SIGMETs). This change is described in detail in AIC 14/13, but, in summary:

- SIGMETs had previously been corrections to GFAs; now they are ICAO-compliant warnings of significant weather events.
- SIGMETs now cover FIRs, rather than a GFA regions.

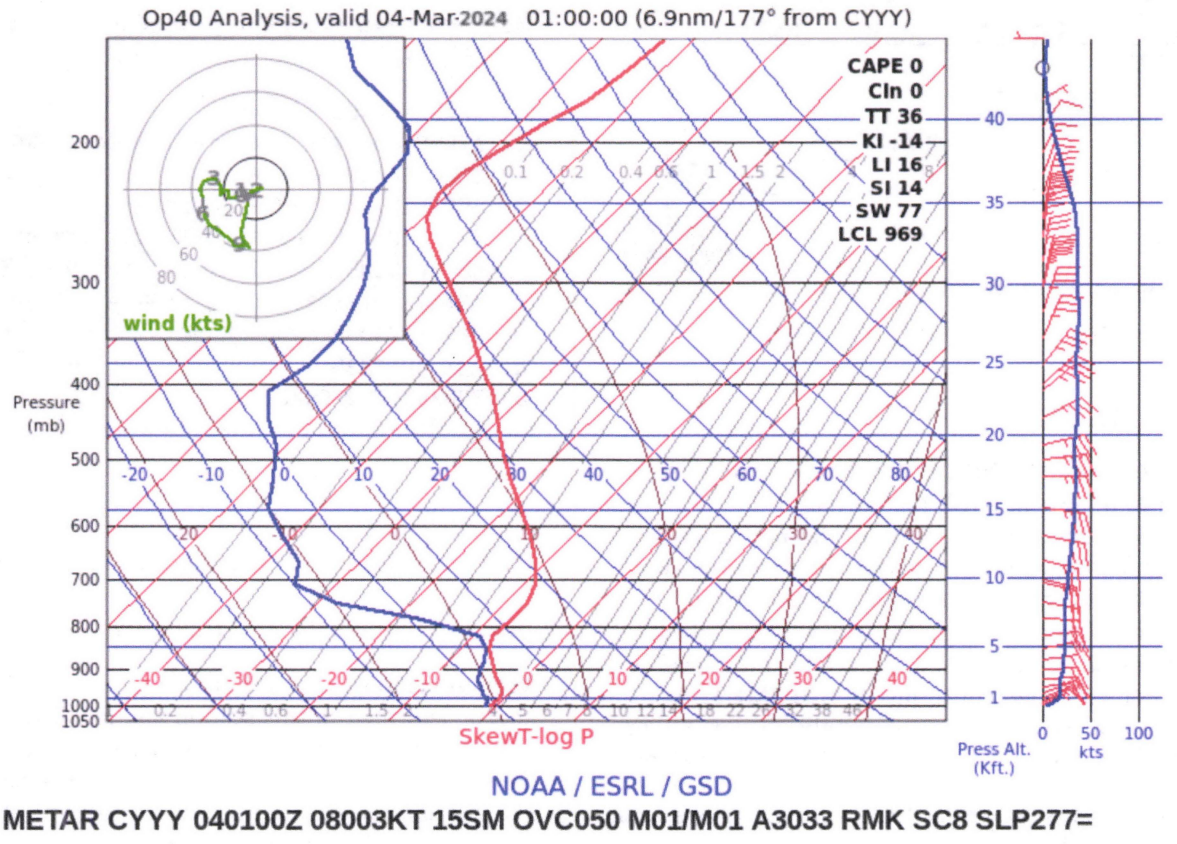


Figure 5.13: Skew-T and associated METAR

- two versions of each SIGMET are now issued: one for national use, and one in standard ICAO format. The primary difference is that the ICAO format simply quotes a latitude and longitude of a point whereas the national format also includes a description (for example, "25 SW CYYY").
- a SIGMET now lasts for exactly 4 hours. If it has not been cancelled before the 4 hour limit, it is tacitly cancelled at that time.

SIGMETs and AIRMETs (section 5.4.6) are issued when a dangerous weather phenomenon has been observed or is forecast.

A SIGMET is issued if the meteorological condition could affect the safety of aircraft in a particular area. These conditions include thunderstorms, severe turbulence, severe icing, freezing rain, severe mountain wave, low level wind shear, heavy dust storm, heavy sandstorm, radioactive cloud, volcanic ash or tropical cyclone.

Exercise 35 *Interpret the following SIGMET (note that line numbers have been added to simplify the explanation—they are not in the original SIGMET).*

```
1. WSCN22 CWAO 160539
2. CZEG SIGMET A1 VALID 160535/160935 CWEG-
3. CZEG EDMONTON FIR
4. SEV TURB OBS WTN 20 NM OF LINE /N5028
   W11524/45 S CYBA - /N5115 W11404/10 N CYYC
   FL180/220 MOV ESE 10KT WKNG
5. RMK GFACN32 GFACN31
```

As with most forecasts and reports, the SIGMET is published in a format that needs some deciphering, as exercise 35 relating to a SIGMET in national format illustrates.

Figure 5.14 illustrates the numbering of a SIGMET. It is assumed that the dangerous phenomenon started at 15:00Z and stopped at 04:40Z the next day. The 'A' in the SIGMET numbering identifies the ongoing phenomenon. All 26 letters of the alphabet are shared between the FIRs in alphabetical order, except the letter 'T' which is reserved for test purposes. The numbers increment on each SIGMET (i.e., every 4 hours) and are reset to 1 at the first SIGMET issued after 00:00Z. Because the condition persisted for more than 4 hours, 'A2' was issued at 19:00Z, and 'A3' at 23:00Z.

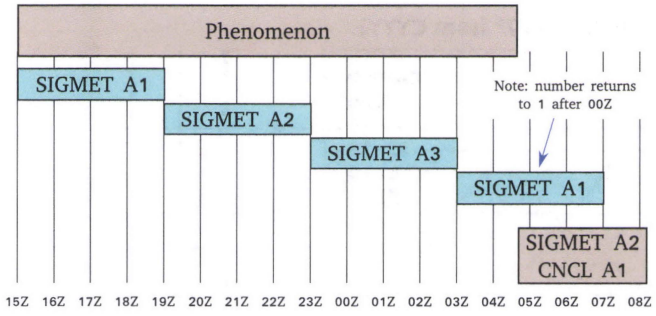


Figure 5.14: SIGMET Numbering

5.4.6 AIRMETs

While the purpose of a SIGMET changed from being a correction to a GFA in 2013, the *Airman's Meteorological Advisory*[4] (AIRMET) did not change, although it followed the GFA in being reported in two formats: international and national. An AIRMET notifies pilots of potentially hazardous weather which was not foreseen in the GFA, and for which the level of danger is not great enough to justify a SIGMET. As with a GFA, an AIRMET describes only phenomena up to FL240. Phenomena covered by an AIRMET include:

- IFR conditions (less than 1000 ft ceiling or less than 3 miles visibility)
- Surface winds of 30 knots or more over a large area
- Moderate turbulence (not associated with convective clouds)
- Moderate icing (not associated with convective clouds)
- Thunderstorms (isolated rather than appearing as a line)

As with a SIGMET, an AIRMET is valid for four hours unless cancelled. The format of an AIRMET is very similar to that of a SIGMET as exercise 36 illustrates. The letters used to identify AIRMETs overlap those for SIGMETs and so, at one time, there could be an AIRMET P2 and an unrelated SIGMET P2 active. AIRMET numbering follows the same pattern as illustrated in figure 5.14, with the number starting again at 1 when 00:00Z is passed. As with a SIGMET, the letter 'T' is reserved for test reports.

Exercise 36 *Interpret the following AIRMET (line numbers have been added to assist with the description—they are not present in the original AIRMET).*

```
1. WACN35 CWEG 140149
2. AIRMET D1 VALID 140145/140545 CWEG-
   CZEG EDMONTON FIR
3  SFC VIS 1/2-2SM FZFG/BR -
   OVC CLD 100-400/1000FT FCST WTN 45
   NM OF LINE /N6927 W13841/120 N CYOC -
   /N7112 W13825/150 NW CYUB - /N7058
   W13311/90 N CYUB QS NC
4. RMK GFACN35
5. END/WACN22/CWAO
```

[4]Or *Aviation Weather Advisory*. The NAV CANADA and Transport Canada documentation is ambiguous about the expansion of the AIRMET acronym.

5.5 Maps & Prognostic Charts

5.5.1 Symbols & Decoding

Various symbols are used on one or more of the graphical charts described in this section and a collection of the more common ones is given in figure 5.15. In addition to these, there are additional symbols used to summarise the information from a particular reporting station on a surface analysis or upper air (constant pressure) chart and for describing wind speed and direction.

Station Reporting on Surface Analysis Chart

Figure 5.16 illustrates a typical station recording on a surface analysis chart. The dot in the centre represents the position of the station and the other symbols always take the same position relative to the dot:[5]

- The wind arrow shows the direction (in this case from the north east) and strength of the wind at the surface as described below. In the example the wind is between 20 and 24 knots.
- The number in the 2 o'clock position (013) records the last three digits of the atmospheric pressure in decapascals. In this case the atmospheric pressure is 10013 decapascals or 1001.3 hectopascals. Note that on a surface analysis chart the last three digits are always used and this differs from the way the same information is conveyed in a METAR.
- The symbol in the 3 o'clock position records how the pressure has changed in the last hour. In the example it has dropped (downward sloping line) by 1.1 hectopascals.

[5]In practice only a few of the positions are normally completed.

Moderate Turbulence	Severe Turbulence	Hail
Moderate Icing	Severe Icing	Haze
Rain	Drizzle	Mist
Rain Shower	Freezing Rain	Fog
Snow	Snow Shower	Fog + Rime
Heavy Rain Shower	Squalls	Ice Pellets
Shower of Ice Pellets	Heavy Thunderstorm with hail	
Thunderstorm	Heavy Thunderstorm with rain or snow	
Cold Front	Warm Front	Trowal
Occluded Front	Stationary Front	Lightning

Figure 5.15: Weather Charts: Commonly-Used Symbols

- The symbol in the 5 o'clock position records the weather (with a symbol taken from figure 5.15) an hour ago. In this case it was misty.

- The symbol in the 6 o'clock and 12 o'clock positions records the types of high-level, medium-level and low-level clouds. In the example there are no symbols in the 12 o'clock position but a line indicating stratus in the 6 o'clock position.[6]

- The symbol in the 7 o'clock position (23) gives the dew point (23°C).

- The leftmost symbol at 9 o'clock (12) gives the current visibility in hundreds of metres—1.2 km.

- The rightmost symbol at 9 o'clock gives the current weather using a symbol from figure 5.15. In the example, it is raining.

- The symbol in the 10 o'clock position gives the current temperature (25°C).

[6]Many symbols are used to represent the different cloud types—a knowledge of them is not required for the Transport Canada examination and they are not reproduced in this book.

Station Reporting on Upper Air Chart

The symbols used on an upper air (constant pressure) chart for weather station reports are similar to, but simpler than, those on the surface analysis charts. The wind direction and speed symbol is the same and numbers at 10 o'clock and 8 o'clock represent the temperature and dew point respectively.

Wind Speed & Direction

As illustrated in figure 5.16, wind direction and speed is represented on several charts by an arrow with barbs ("feathers"). The arrow direction indicates the direction of the wind and the barbs signify its speed in a form not dissimilar to Roman numerals:

- Each solid triangle represents 50 knots; see, for example, the arrow just above Ⓒ in figure 5.17.

- Each standard barb represents 10 knots.

- Each small barb represents 5 knots.

Thus a wind of between 115 and 120 knots would be represented by two triangles (2 × 50 knots), one standard barb (10 knots) and one small barb (5 knots).

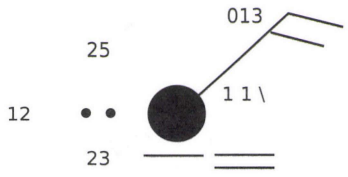


Figure 5.16: Station Weather on Surface Analysis Chart

5.5.2 Surface Analysis Chart

Surface analysis charts are produced four times each day, at 00:00Z, 06:00Z, 12:00Z and 18:00Z. They show the positions of high and low pressure systems and fronts at sea level (i.e., they are constant altitude charts rather than constant pressure charts). Pressure levels are indicated by isobars at 4 hectopascal intervals as described on page 58. The terms *NEW* and *QS* are used to indicate newly-formed and quasi-stationary features. Quasi-stationary features are ones that have not changed in the last 6 hours.

If an area of low pressure has existed for more than 6 hours, then its track is shown as a series of "breadcrumbs" indicated by circles joined by dashed lines with its central pressure given at each breadcrumb. This allows you to visualise the movement and changes in the depth of the low pressure system.

5.5.3 Upper Air Analysis Charts

NAV CANADA issues constant pressure (upper air analysis) charts prepared by Environment Canada for the 850 hectopascal (corresponding to about 5,000 ft ASL), 700 hectopascal (about 10,000 ft ASL), 500 hectopascal (about 18,000 ft ASL) and 250 hectopascal (about 34,000 ft ASL) levels twice each day, at 00:00Z and 12:00Z.

The concept behind a constant pressure chart is described on page 58, where an isobar (joining all points with the same atmospheric pressure at a given height—normally sea level) is contrasted with a contour (joining all points with the same height at a given atmospheric pressure).

The primary lines on an Upper Air Chart are contours, but other information is also contained on the chart:

- On the 850 and 700 hectopascal charts, dotted lines indicate temperature in degrees Celsius.
- On the 500 hectopascal chart, the thickness of the 1000 to 500 hectopascal layer is shown. Larger thicknesses indicate warmer air.
- On the 250 hectopascal chart, the wind speed is shown: this can be used to locate the Jet Streams.

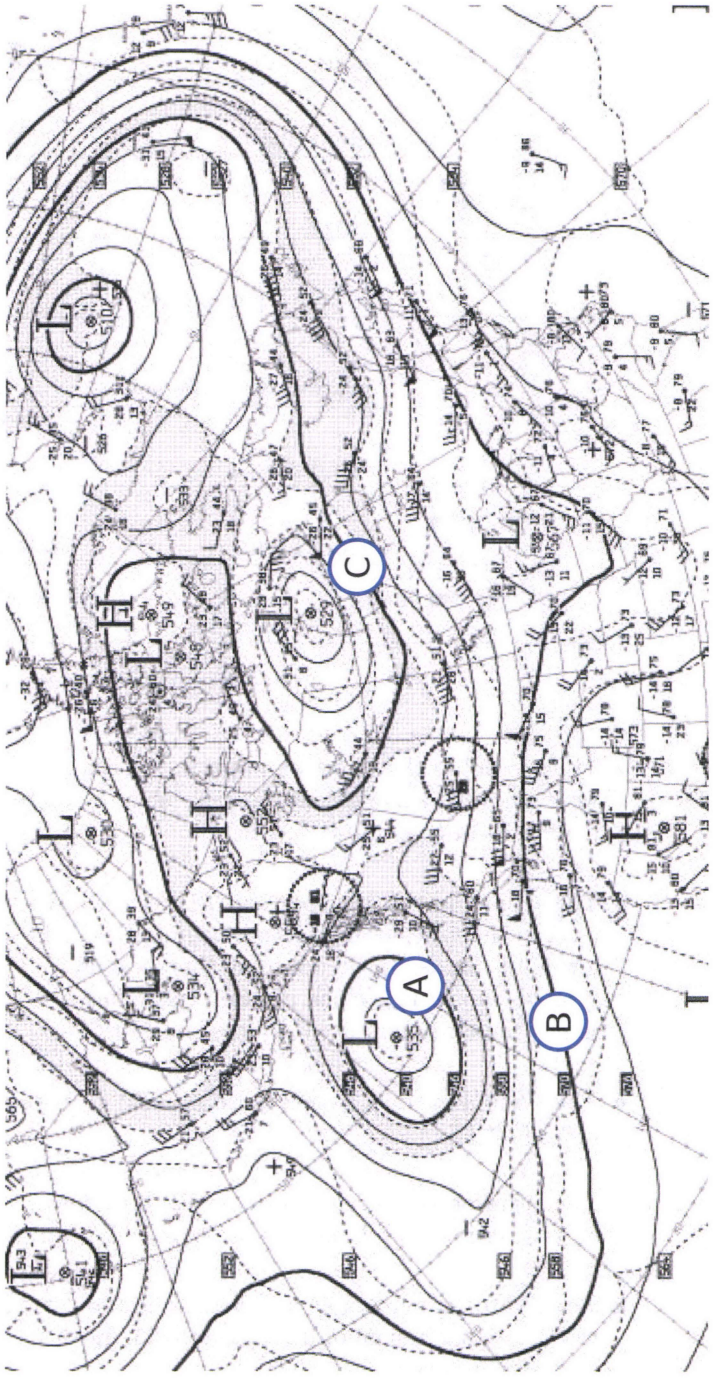


Figure 5.17: Part of a 500 mb (hP) Upper Air Chart

Figure 5.17 contains part of a 500 hectopascal upper air chart issued by NAV CANADA.[7]

Exercise 37 *Consider figure 5.17. What is the meaning of the circled cross with the number 535 at Ⓐ?*

Exercise 38 *Consider figure 5.17. What is the meaning of the line marked 570 at Ⓑ?*

Exercise 39 *Consider figure 5.17. What is the meaning of the arrow and associated numbers just above Ⓒ?*

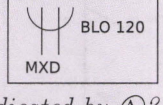
5.5.4 Significant Weather Prognostic Chart

As its name suggests, the *Significant Weather Prognostic Chart (Upper Air) 700-400 mb* is a forecast issued to warn pilots of significant weather in the middle levels (between 700 and 400 hectopascals—about 10,000 to 24,000 ft ASL). An additional Significant Weather Prognostic Chart is created for the North Atlantic, covering from the surface to the 400 hectopascal level.

These charts are issued four times each day and are distributed at about 02:10Z, 08:15Z, 14:25Z and 19:40Z for 12:00Z, 18:00Z, 00:00Z and 06:00Z respectively. So, these charts are distributed about 10 hours before their valid time. They show forecast surface positions of pressure centres and fronts, areas of significant cloud, areas of turbulence and icing, freezing levels and, where appropriate, positions of tropical storms and hurricanes.

Figure 5.18 gives an example of a Significant Weather Prognosis chart, valid for 06:00Z on 25th May 2009.

Exercise 40 *Consider the Significant Weather Prognosis Chart given in figure 5.18. What is the meaning of the box*



indicated by Ⓐ?

[7] For clarity only part of the chart is included. The circled letters are present so that they can be referred to in exercises—they are not on the original chart.

Exercise 41 *Consider the Significant Weather Prognosis Chart given in figure 5.18. What is the meaning of the heavy dotted line marked Ⓑ?*

5.6 Answers to Exercises

This section contains possible answers to the exercises in this chapter.

Exercise 27

The `VC` on the front of VCSHRAGR means "in the vicinity". The `SH`, `RA` and `GR` symbols can be read from figure 5.4 to mean "showers", "rain" and "hail". This group therefore means that there are rain showers with hail in the vicinity.

Figure 5.4 indicates that `MI` means "shallow" and `FG` means "fog". MIFG therefore means that there is shallow fog at the aerodrome.

Exercise 28

The term CCA in the METAR is the key here: it indicates that this is a correction to an earlier one. If appears that the cloud conditions at 01:00Z were initially given as FEW140 (few clouds at 14,000 ft), but that this should have been FEW041 SCT140 (few at 4,100 ft and scattered at 14,000 ft).

Exercise 29

This is a standard METAR (rather than a special report) issued for Churchill (CYYQ) at 16:00Z on the 28th of the month. Winds are from the north-north-west (330° true) at 15 knots, gusting to 20 knots. Visibility is 15 statute miles. There is drifting snow (DRSN). Less than $\frac{1}{8}$ of the sky is covered with cloud (SKC), the temperature is −28°C and the dew point is −33°C. The sea level pressure is 30.45″ Hg. The remarks contain the information that the sea level pressure is 1031.7 hP.

Exercise 30

Clearly Ottawa is lying in the influence of a high pressure (30.40″ Hg) but over the past three hours the pressure has been dropping and the winds veering to become more northerly. A low pressure moving from west to east south of Ottawa would account for both the drop in pressure and the change in the direction of the winds.

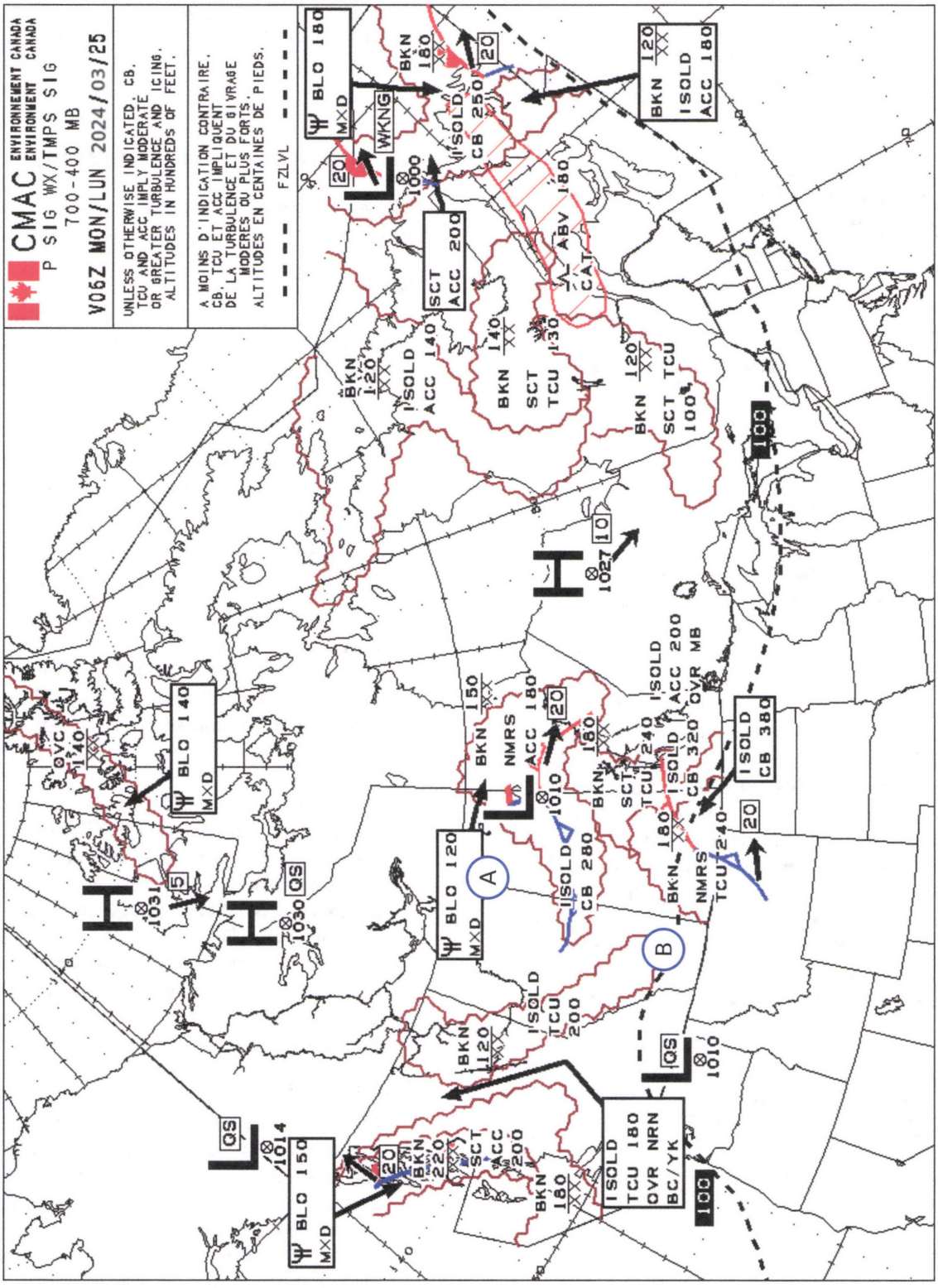


Figure 5.18: A Significant Weather Prognosis Chart—see Exercise 35

Exercise 31

Pilot: Québec Radio, this is Foxtrot Alfa Bravo Charlie with a PIREP.

Québec Radio: Alfa Bravo Charlie, go ahead.

Pilot: Foxtrot Alfa Bravo Charlie 34 east of YMX on the 072 radial at 13:15Z, 6,000 ft, PA28, stratus overcast topped at 5,000 ft, no cloud above, 10 degrees Celsius, wind from 320 magnetic at 24, no turbulence, no icing.

Québec Radio: Alfa Bravo Charlie, PIREP copied.

Exercise 32

```
UACN10 CYQB 141321
UL
UA /OV YMX072034 /TM 1315 /FL060
/TP PA28 /SK OVC050 /TA 10 /WV 32024 /TB NIL
```

The aircraft's location has been given as a bearing (072) and distance (34) from the YMX VOR and the cloud level has been encoded at OVC050 indicating that the *tops* are at 5,000 ft ASL. If the PIREP had included the cloud bases at, say, 3,000 ft then this would have been encoded as 030OVC050.

Exercise 33

This is an amended (AMD) TAF for Edmonton airport (CYEG) issued at 19:12Z on the 15th of the month. It is valid from the time it was issued and covers the period until 18:00Z on the 16th of the month. The forecast is for winds to be from the west (true) at 15 knots, gusting to 35 knots. Visibility is forecast to be 3 statute miles in light thunderstorms and rain with scattered cloud at 800 ft AGL and overcast cumulonimbus cloud at 1,500 ft AGL. For periods of less than an hour between 20:00Z and 23:00Z the winds might back to 250° true and increase in speed to 35 knots gusting to 45 knots. In this case visibility will reduce to 1 statute mile with thunderstorms, rain and snow pellets with the sky overcast at 800 ft AGL with cumulonimbus cloud. There is a 30% probability that, between 20:00Z and 23:00Z, the visibility will drop further to half a statute mile with heavy thunderstorm, rain and snow pellets. From 00:00Z on the 16th of the month the wind is forecast to veer to 330° true and blow at 15 knots, gusting to 25 knots. The visibility will increase to more than 6 statute miles and the sky will be clear. Between 09:00Z and 10:00Z on the 16th of the month the wind is forecast to reduce to 5 knots. The next forecast will be issued before 21:30Z on the 15th of the month.

Exercise 34

The time of 04:00Z lies in the range 2100-0600Z and so the wind direction, wind speed and temperature are taken from middle line of the FD. These are 244747. As this is above 24,000 ft, the ± is omitted from the temperature which is assumed to be negative. The wind direction is less than 36 and so 50 has not been added to it; the wind direction can therefore be read directly as 240°T. As 50 has not been added to the wind direction, the wind speed can also be read directly as 47 knots. The forecast temperature is −47°C. Note that this forecast is valid at 00:00Z but is used for the whole period from 21:00 to 06:00Z.

Exercise 35

This SIGMET can be interpreted as follows:

Line 1. The first two letters (WS) identify this as a SIGMET for other than volcanic ash (SV) or tropical cyclone (WC). "CN" indicates that the SIGMET refers to Canada, and 22 is a sequence number. "CWAO" is used for all Canadian SIGMETs. The "160539" group indicates that the SIGMET was issued on the 16th of the month at 05:39Z.

Line 2. The '1' in the identifier 'A1' indicates that this is the first SIGMET reporting this phenomenon.

Line 3. This defines the FIR where the phenomenon is happening: Edmonton.

Line 4. This describes the phenomenon. In plain English it says that severe turbulence has been observed within 20 nautical miles of a line from 50°28′N 115°24′W (which is 45 miles south of CYBA) to 51°15′N 114°04′W (which is 10 miles north of CYYC) between flight levels 180 and 220. This line is moving east-southeastward at 10 knots and is weakening,

Line 5. In the national format, the remark line always contains a list of the GFA regions affected by the phenomenon: in this case GFACN32 (Prairies) and GFACN31 (Pacific).

Exercise 36

The AIRMET can be interpreted as follows:

Line 1. The WACN35 means that this is a warning (W), an AIRMET (A) which was issued in Canada (CN). CWEG indicates that this was issued in western Canada (CWUL would have indicated eastern Canada). The

140149 indicates that the AIRMET was issued on the 14th of the month at 01:49Z.

Line 2. This is the first AIRMET for this phenomenon (D1) and it is valid for the 4 hour period from 01:45Z. It concerns the Edmonton Flight Information Region.

Line 3. This describes the actual conditions: surface visibility of $\frac{1}{2}$ to 2 statute miles with freezing fog and mist. Overcast low cloud is forecast within 45 nautical miles of a line from 120 miles north of CYOC (Old Crow) to 150 miles northwest of CYUB (Tuktoyaktuk) to 90 miles north of CYUB. This phenomenon is quasi-stationary.

Line 4. The PIREP affects the GFACN35 GFA (Yukon and Northwest Territories).

Line 5. This indicates the end of the PIREP.

Exercise 37

The circled cross with the number 535 at Ⓐ represents the point where, in that area, the 500 hectopascal pressure appears at its lowest level above sea level—535 decametres (i.e., 5,350 metres or 17,552 ft). Note that it is within a contour labelled 540 and so the circled point is literally the bottom of the hill.

Exercise 38

The line marked 570 at Ⓑ joins all points where the 500 hectopascal pressure level will be at 570 decametres (i.e., 5,700 metres or 18,700 ft) above sea level.

Exercise 39

This is a wind arrow indicating that the wind is from the west. There is one triangle at the end of the arrow indicating that the wind speed is between 50 and 54 knots (see page 109). The temperature at the reporting station is $-26°C$ and the difference between the temperature and the dew point is 22 Cdeg (i.e., the dew point is $-48°C$). The third number (45) indicates the height of the 500 hectopascal level: 4,500 metres or about 14,764 ft. Note that this is significantly lower than the nominal height of the 500 hectopascal level (18,000 ft) and this is confirmed by the reading being close to a low pressure.

Exercise 40

The symbol indicates moderate icing (see figure 5.15) so the box means that in the area portrayed moderate mixed icing is forecast below 12,000 ft ASL.

Exercise 41 As indicated in the key in the top-right hand corner of the chart, this indicates the freezing level as being at 10,000 ft ASL.

Chapter 6

Pre-Flight Preparation

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6.1 Introduction

Whether a flight is made for professional or recreational purposes, navigation is essential. The techniques used to plan and navigate a trip have changed dramatically over the past couple of decades:

- Planning used to involve drawing lines on paper maps, measuring distances and angles, and manually calculating headings and ground speeds. This process has largely been replaced by computers and tablets with databases of all navigation devices, aerodromes, airways, etc. These applications automatically access the upper wind forecasts, recommend altitudes at which to fly and file the resulting flight plan without the pilot having to contact Flight Services or complete the online form.
- In the 1990s and even early 2000s, navigation relied on ground-based radio stations—VORs, NDBs, DMEs, LORAN—and, while many of these still exist, most pilots today would feel uncomfortable taking off without at least a handheld GPS receiver. The availability of cheap, reliable and extremely accurate GPS receivers has made navigation for many pilots as simple as pressing the *GOTO* button and following a line on a moving map.

There are dangers and limitations in an unthinking adoption of computer planning programs and GPS navigation; this book therefore treats navigation in four parts:

1. **Flight Preparation,** which is needed whatever navigation aids will be used in the air. This is the purpose of this chapter.
2. **Satellite-based Navigation,** which is how most flights will the flown. This is described in chapter 7.
3. **Ground-based Navigation,** which is needed to compensate for the risks associated with relying completely on satellite-based navigation. Chapter 7 also describes ground-based aids.
4. **Deduced Reckoning,** which, although unlikely to be used much in practice, is included on the Transport Canada CPL syllabus. This is covered in chapter 8.

   DED (deduced) reckoning is the method of navigation that will work when all the electronic devices have failed. It can also be extremely accurate and, frankly, fun to fly.

6.2 Latitude & Longitude

6.2.1 Great Circles

The airports between which we fly are located on the surface of the spherical earth. The shortest route between two points on the surface of a sphere is known

as the great circle or orthodromic route. Figure 6.1 illustrates the great circle across Canada.

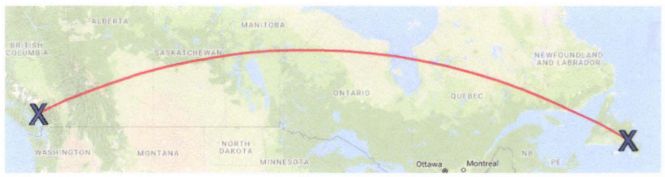

Figure 6.1: Great Circle Route Across Canada

There was interest in 2018 in finding the longest great circle routes which are completely over land and completely over water. This problem was answered by researchers in Ireland and India. The more surprising result is the longest route completely over water: from Sonmiani in Pakistan to Kamchatka Krai in Russia (32,089.7 km). The longest route completely over land is less surprising and runs from Jinjiang in China to Sagres in Portugal (11,241.1 km).

6.2.2 Locating Position by Latitude & Longitude

Lines of longitude run from the North to the South Pole and are numbered by their angle from the prime meridian, the line of longitude that runs through Greenwich, London (see figure 6.2 and imagine a Terry's Chocolate Orange). Lines of longitude in Canada all lie to the west of Greenwich, so the longitude of any place in Canada is specified as $x°$ west of Greenwich.[1]

The history of the prime meridian is interesting. The first person to define its position, around the year 120, was Claudius Ptolemy who based it on the "Fortunate Isles" in the Atlantic (probably what we now call the Cape Verde islands). The idea was that the whole of the known world should be east of the meridian. Since 1800 most navigators have used tables based on the meridian being at the Royal Observatory in Greenwich, but there have been numerous attempts to move it from London to other cities. In October 1884 there was a conference in Washington DC, USA, at which the Greenwich Meridian was finally selected by delegates. The point is that, while the circle from which latitude is measured, the equator, is logical, the meridian from which longitude is measured is arbitrary—it could be anywhere.

Latitude is measured by an angle at the centre of the earth measured upwards or downwards from the equator. All of Canada lies north of the equator and so all latitudes in Canada are expressed as $y°$ north.

[1]Note that this is not true of the USA where parts of Alaska's Aleutian Islands are east of London. Indeed, Alaska is the northernmost, westernmost and easternmost state of the USA. "What is the easternmost state in the USA?" is a useful trivia question.

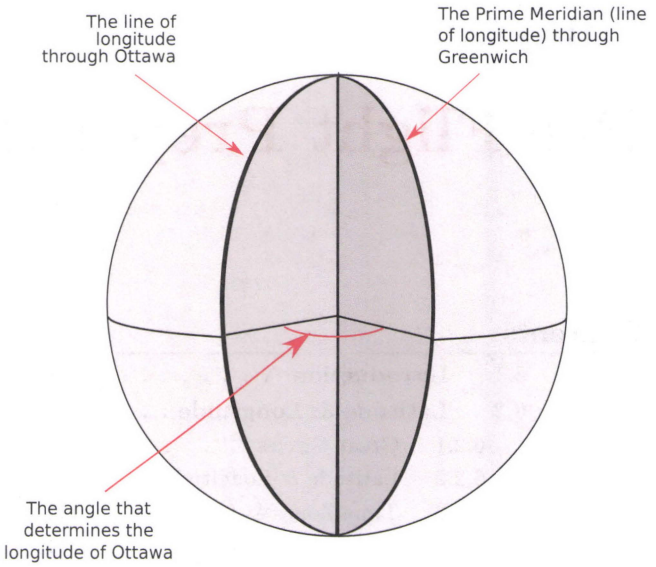

Figure 6.2: Measurement of Longitude

Specifying the latitude and the longitude of any place on the surface of the earth gives its position precisely.

Angles of latitude and longitude may be expressed in:

1. degrees, for example 123.56°.
2. degrees and minutes, for example 123° 45.677′. There are 60 minutes in a degree.
3. degrees, minutes and seconds, for example 123° 56′ 12.3″. There are 60 seconds in a minute.

Vancouver International Airport, for example, can be expressed as being 49.1919° north or 49° 11.52′ north or 49° 11′ 31″ north. Make sure that you can convert between these formats using your electronic flight calculator.

Exam Hint 12 *Note that some electronic flight calculators cannot handle angles larger than 90 degrees. Make sure that you are familiar with the limitations of your calculator* before *you go into the examination room.*

Exam Hint 13 *Canada lies to the west of Greenwich and therefore longitude increases from right to left on a map. If you are looking, for example, for the 75°40′ line of longitude, you may start at the 75° line. Reading in the normal manner, you might move to the right on the chart. In fact, the 75°40′ line of longitude lies to the* left *of the 75° line on your chart.*

6.2.3 Time Zones & Longitude

The sun appears to travel continuously westward in the sky. Before the days of trains, when travel was still comparatively slow, local time would be set in each town: midday being when the sun was overhead.

Every town having its own time became impractical when the railways appeared and timetables were being published. It was therefore decided that the earth should be divided into *time zones:* zones within which all towns would have the same clock time.

In the 19th century Lewis Carroll, best known for his Alice stories, foresaw the problem with time and date around the earth. He imagined a far future when flying machines existed which could fly around the earth at the same speed as the sun. If one of these took off in England at midday on Tuesday and flew westwards keeping up with the sun, then whenever the travellers saw someone on the ground and called down "what time is it?", the person on the ground would always respond "midday: look, the sun is overhead". This would continue around the earth until the flying machine arrived back in England. There the people on the ground would still say that it was midday, but now on Wednesday. Somewhere the day had changed from Tuesday to Wednesday! Today we call this boundary the date line, and it produces the unexpected ending to Jules Verne's novel *Le tour du monde en quatre-vingts jours.*

As the earth takes 24 hours to revolve 360° about its axis, it takes an hour to revolve 15°. We have, therefore, divided the earth into 24 time zones, each approximately 15° of longitude wide. All towns within the same time zone keep the same clock time. In practice, time zones are not exactly 15° wide; instead, their edges are aligned to political borders.

6.2.4 UTC & Local Time

For some of the techniques described later in this chapter it is important to know the actual local time at a particular location—not the wall clock time zone time, but the actual time according to the position of the sun.

Natashquan, Ottawa and Thunder Bay for example, are all in the same time zone. Simultaneously asking people in each of these cities the time would cause them to look at their watches and, for example, reply 19:00, 19:00 and 19:00 (respectively). However, it is likely that the sun has already set in Natashquan while still in the sky in Thunder Bay. Clearly the time on a person's watch is not the "correct" time according to the sun.

Natashquan is 61°47′ west of Greenwich whereas Thunder Bay is 89°19′ west of Greenwich. They are therefore 27°32′ apart. As the sun traverses 15° of longitude every hour, it takes $\frac{27.53}{15} = 1.84$ hours (1 hour 50 minutes) to get from Natashquan to Thunder Bay.

This indicates how the local time can be found at any point given:

1. the longitude of the point (how far east or west of Greenwich it is)
2. the current Zulu time (i.e., the time at Greenwich without correction for summer time)

Exercise 42 *The longitude of the airport at Rimbey, Alberta is* 114°14′ *west. The Zulu time is currently 12:34. What is the local time in Rimbey?*

Answers to the questions in this chapter begin on page 126.

6.2.5 Twilight Charts

Twilight is the period of time that occurs as the sun is setting or rising. There are at least three definitions of twilight:

1. **Civil Twilight** begins in the morning when the centre of the Sun is less than 6° below the horizon, and ends at sunrise. Evening civil twilight begins at sunset and ends when the centre of the Sun is more than 6° below the horizon.
2. **Nautical Twilight** is defined as the period when the centre of the Sun is more than 6° below the horizon but less than 12°.
3. **Astronomical Twilight** is defined as the period when the centre of the Sun is more than 12° below the horizon but less than 18°.

For aviation purposes, "twilight" means "Civil Twilight" and the General Section of the AIM contains charts that can be used to determine the time of twilight—see figure 6.3. To use these tables to calculate the true local time of twilight, enter the table at the top with the current date and move downwards until you reach your current latitude. The true local time for twilight can then be read off by moving horizontally to the scales along the sides.

Exercise 43 *Using the red line in figure 6.3 (or the equivalent chart from the AIM), determine the local time of morning twilight on 20th April at an airport that is at* 55° *N.*

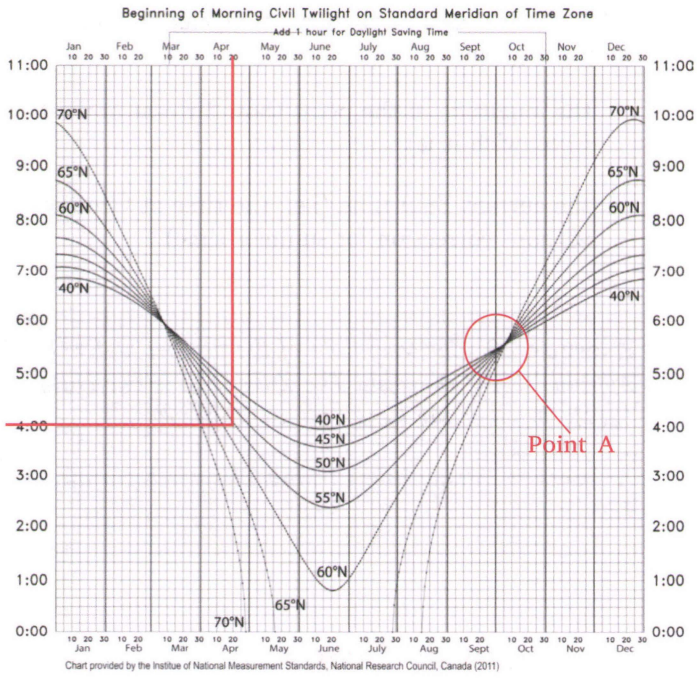

Figure 6.3: Morning Twilight (From AIM)

The formula for calculating twilight at any particular point on the earth's surface at a given date is complex but most aviation calculators provide a means of finding it.

Exercise 44 *What is the significance of the point circled and marked as Point A in figure 6.3 where all the lines cross?*

6.2.6 The Untrustworthy Compass

In the far north of Canada, close to the magnetic north pole, a magnetic compass becomes unreliable, in part because of the increased dip in the earth's magnetic field; see section 10.2.3 on page 210. With ubiquitous GPS this is not generally a problem for navigation, but setting the aircraft's heading indicator at intervals requires a method other than aligning it with the compass. There are several ways of determining direction in these conditions:

- **Celestial Navigation**

  The stars have been a means of determining direction for thousands of years, particularly for ships at sea and aircraft on over-ocean flights. This topic is not required for the Transport Canada examination, although it can be an interesting one to study.

- **Using Area Navigation (RNAV) Equipment**

  Area Navigation (RNAV[2]) is a common term in IFR flight and refers to an aircraft's ability to navigate using ground-based or satellite transmitters other than just directly TO or directly FROM a ground-based beacon. This type of navigation works without the use of the magnetic compass and can be used in the far north.

  For example, Transport Canada's extended-surveillance Dash-8 aircraft commonly fly in the Northern Domestic Airspace and the operating procedures require the use of the RNAV tied to the aircraft systems to determine True Heading. The Heading Indicator must be disconnected from the magnetic flux gate because that relies on the earth's magnetic field and is unreliable so far north. Once disconnected, it has to be manually reset every 30 minutes to account for the change of longitude. The operating procedures also include instructions to prevent the autopilot from making excursions while these changes are made.

  During instrument approaches, the aircraft needs to follow a track accurately to align with the runway, and the operating procedures recommend either using the bearing of the sun (see next section) or an ADF pointing to an NDB. When an ADF is used, the pilot has to be aware of its limitations (see section 7.6.9 on page 146 and the procedure is not permitted if there is a thunderstorm within 50 nautical miles.

- **Calculating the Sun's True Bearing**

  This topic has been dropped from Transport Canada's syllabus, presumably because few pilots in the 21st Century use the sun as a navigation device. However, it is a good exercise and I find that students enjoy the calculation, even though it will now not appear on the written examination.

  The assumption is that you're flying in an area in the north where your magnetic compass is unreliable and you need to reset your heading indicator which has drifted. If you:

  1. know your latitude and longitude (from a GPS or by observing a landmark over which you're flying and finding it on the map);
  2. know the UTC (Zulu) time and date—by consulting your GPS or wristwatch;
  3. have a book of pre-computed tables with you;
  4. can see the sun

[2]The term used to be "random navigation": hence the acronym.

DATE \ HOURS	0800	0808	0816	0824	0832	0840	0848	0856	0904	0912	0920	0928	0936	0944	0952
DEC 31	126.4	128.0	129.6	131.3	132.9	134.5	136.2	137.9	139.5	141.2	142.9	144.6	146.4	148.1	149.9
JAN 10	125.0	126.6	128.2	129.8	131.5	133.1	134.8	136.4	138.1	139.8	141.5	143.3	145.0	146.8	148.5
JAN 20	123.3	124.9	126.6	128.2	129.9	131.5	133.2	134.9	136.6	138.3	140.1	141.8	143.6	145.3	147.1
JAN 30	121.6	123.2	124.9	126.6	128.2	129.9	131.6	133.3	135.1	136.8	138.6	140.4	142.2	144.0	145.8
FEB 9	119.9	121.5	123.2	124.9	126.6	128.3	130.1	131.8	133.6	135.4	137.2	139.0	140.8	142.7	144.5
FEB 19	118.2	119.9	121.6	123.3	125.1	126.8	128.6	130.4	132.2	134.0	135.8	137.7	139.6	141.5	143.4
MAR 1	116.6	118.3	120.1	121.8	123.6	125.4	127.2	129.0	130.9	132.7	134.6	136.5	138.4	140.4	142.4
MAR 11	115.1	116.8	118.6	120.4	122.2	124.0	125.8	127.7	129.6	131.5	133.5	135.4	137.4	139.4	141.5
MAR 21	113.6	115.3	117.1	118.9	120.8	122.7	124.5	126.5	128.4	130.4	132.4	134.4	136.4	138.5	140.6
MAR 31	112.0	113.9	115.7	117.5	119.4	121.3	123.2	125.2	127.2	129.2	131.2	133.3	135.4	137.6	139.8
APR 10	110.5	112.3	114.2	116.1	118.0	119.9	121.9	123.8	125.9	127.9	130.0	132.2	134.4	136.6	138.8
APR 20	108.9	110.7	112.6	114.5	116.4	118.4	120.4	122.4	124.5	126.6	128.7	130.9	133.2	135.5	137.8
APR 30	107.2	109.1	111.0	112.9	114.8	116.8	118.8	120.9	123.0	125.1	127.3	129.5	131.8	134.2	136.6
MAY 10	105.5	107.4	109.3	111.2	113.1	115.1	117.1	119.2	121.3	123.5	125.7	128.0	130.3	132.7	135.2
MAY 20	103.9	105.7	107.6	109.5	111.4	113.4	115.5	117.5	119.7	121.9	124.1	126.4	128.7	131.2	133.6
MAY 30	102.3	104.2	106.0	107.9	109.9	111.9	113.9	116.0	118.1	120.3	122.5	124.8	127.2	129.6	132.1
JUN 9	101.1	102.9	104.8	106.7	108.6	110.5	112.6	114.6	116.7	118.9	121.2	123.5	125.8	128.2	130.7
JUN 19	100.3	102.1	103.9	105.8	107.7	109.6	111.7	113.7	115.8	118.0	120.2	122.5	124.8	127.2	129.7
JUN 29	99.9	101.7	103.6	105.4	107.3	109.3	111.3	113.3	115.4	117.5	119.7	122.0	124.3	126.7	129.2
JUL 9	100.2	102.0	103.8	105.7	107.6	109.5	111.5	113.5	115.6	117.7	119.9	122.2	124.5	126.9	129.3
JUL 19	101.1	102.9	104.7	106.6	108.5	110.4	112.4	114.4	116.5	118.6	120.8	123.0	125.3	127.6	130.0
JUL 29	102.5	104.3	106.1	108.0	109.9	111.9	113.8	115.9	117.9	120.0	122.2	124.4	126.7	129.0	131.4
AUG 8	104.5	106.3	108.1	110.0	111.9	113.8	115.8	117.8	119.9	122.0	124.2	126.4	128.6	130.9	133.3
AUG 18	106.8	108.7	110.5	112.4	114.3	116.2	118.2	120.2	122.3	124.4	126.5	128.7	130.9	133.2	135.5
AUG 28	109.5	111.3	113.2	115.1	117.0	118.9	120.9	122.9	125.0	127.0	129.2	131.3	133.5	135.8	138.0
SEP 7	112.4	114.2	116.1	117.9	119.8	121.8	123.7	125.7	127.8	129.8	131.9	134.1	136.2	138.4	140.7
SEP 17	115.3	117.1	119.0	120.9	122.8	124.7	126.6	128.6	130.6	132.6	134.7	136.8	138.9	141.1	143.3
SEP 27	118.2	120.0	121.8	123.7	125.6	127.5	129.4	131.3	133.3	135.3	137.3	139.4	141.5	143.6	145.7
OCT 7	120.9	122.7	124.5	126.3	128.2	130.1	131.9	133.9	135.8	137.8	139.7	141.7	143.8	145.8	147.9
OCT 17	123.3	125.1	126.9	128.7	130.5	132.3	134.2	136.1	138.0	139.9	141.8	143.8	145.7	147.7	149.8
OCT 27	125.4	127.1	128.9	130.6	132.4	134.2	136.0	137.9	139.7	141.6	143.5	145.4	147.3	149.3	151.2
NOV 6	127.0	128.7	130.4	132.1	133.9	135.6	137.4	139.2	141.0	142.8	144.7	146.5	148.4	150.3	152.2
NOV 16	128.1	129.7	131.4	133.1	134.8	136.5	138.3	140.0	141.8	143.6	145.4	147.2	149.0	150.9	152.7
NOV 26	128.6	130.2	131.9	133.6	135.2	136.9	138.6	140.4	142.1	143.8	145.6	147.4	149.2	151.0	152.8
DEC 6	128.6	130.2	131.8	133.5	135.1	136.8	138.5	140.2	141.9	143.6	145.3	147.1	148.8	150.6	152.4

Figure 6.4: A Portion of a Sun's True Bearing Table

then you can calculate the true bearing of the sun. You can then point your aircraft at the sun and set your heading indicator to the calculated (true, not magnetic) bearing. If you are flying in the Southern Domestic Airspace, using magnetic rather than true headings, then you should convert the true bearing to magnetic before setting it on your heading indicator; see section 8.2.15 for an explanation of the difference between magnetic and true bearings.

The steps in the calculation of the sun's bearing are:

- to calculate the correct local time using the technique described in section 6.2.4.
- to consult the pre-calculated tables for the latitude and local date/time and read off the sun's true bearing.
- to point the aircraft into the sun and set your heading indicator to the calculated bearing.
- to resume navigation.

Exercise 45 *At 14:23 Z on 29th June you find yourself over-flying Kuujjuarapik, Québec, airport which is located at 55°17′ North, 77°46′ West. Using the portion of the sun's true bearing table for 55° north, given in figure 6.4, or otherwise, explain how you would reset your heading indicator.*

6.3 Aviation Maps

6.3.1 Map Projections

The world is a sphere and a map is flat, so some distortion is always going to be needed to make a map. These distortions are called projections. With the exception of the VFR Terminal Area (VTA) Chart, the charts used in aviation are so-called *conical* projections.

The technique used is illustrated in figure 6.5:

1. A cone of paper is placed over the earth as shown in the figure in such a way that it cuts the earth at

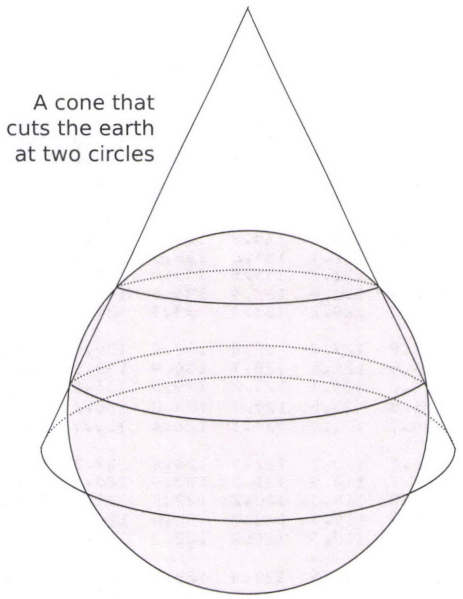

Figure 6.5: Conical Projection 1

two circles of latitude[3] and it is only on these that the map is accurate. The two circles are specified on the map—on the Toronto VFR Navigation Chart (VNC), for example, the circles of latitude where the cone cuts the earth are 41°20′ and 46°40′ north.

2. A light bulb is set up at the centre of the earth and the shadows of the land masses are projected onto the cone. These are traced around on the cone.

3. The cone is split from top to bottom and opened out as shown in figure 6.6. Lines of longitude on the earth have mapped to straight lines meeting at the top. Lines of latitude have become arcs of circles.

4. A rectangular piece of the flattened cone is then cut out and made into a VNC or LO-Chart.

To confirm that this is correct, take a VNC chart and check that the lines of longitude are closer together at the top than at the bottom and look along the lines of latitude to ensure that they are not straight.

The main advantage of a conical projection is that, for short distances, a straight line drawn on the map is quite close to a great circle route. By flying along a straight line drawn on a VNC or LO-chart you are following the shortest distance to your destination. Another advantage is that adjacent maps will fit together without gaps or distortions (since they have effectively been cut from the same flattened cone).

The VTA is the exception in aviation maps. Instead of having being a conical projection created as shown in

[3] A conical projection that cuts the earth at two circles of latitude is sometimes called a *secant* projection. If the cone just touches the earth without cutting it, it is called a *tangent* projection.

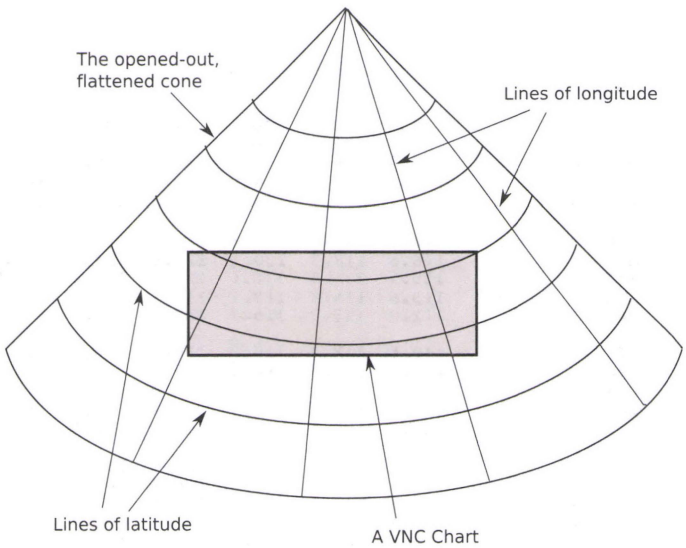

Figure 6.6: Conical Projection 2

figure 6.5 by placing a cone over the earth, it is a cylindrical projection constructed by placing a cylinder around the earth as shown in figure 6.7. The shadows of the ground features are then recorded and the cylinder is split and unrolled.

Exam Hint 14 *If you fly a great circle route other than directly along a line of longitude or around the equator, your track changes at every instant: this is why it is important to measure the desired track at a point close to the centre of the route. This gives a reasonable approximation over short distances. A route where the heading is kept constant is known as a rhumb line or loxodrome route and is a straight line on a cylindrical projection.*

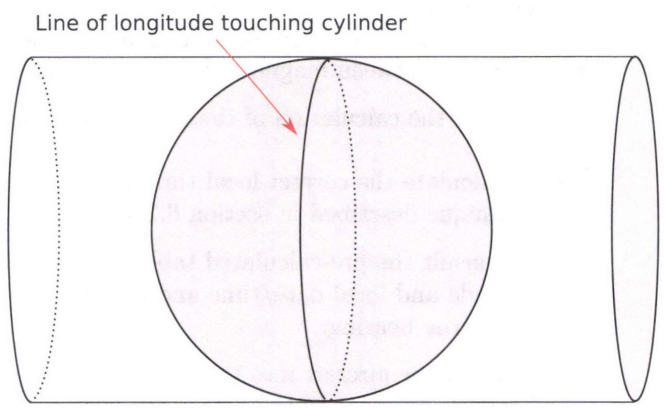

Figure 6.7: Cylindrical Projection

6.3.2 Types of Map

VFR Terminal Chart (VTA)

VTAs are issued for areas where the airspace is particularly busy or complex: Vancouver, Edmonton, Calgary, Winnipeg, Toronto, Ottawa and Montréal. Their scale is twice that of a VNC: 1:250,000, and their peculiarity, as mentioned above, is that they are the only kind of aviation chart that is not a conical projection; instead they are a transverse cylindrical projection as shown in figure 6.7. A VTA covers such a small area that the difference in projection has no practical implications, but it is different from the other charts.

VFR Navigation Chart (VNC)

VNCs are the primary maps for VFR navigation, having many ground features displayed. VNCs are available for the whole of Canada: see figure 6.8.

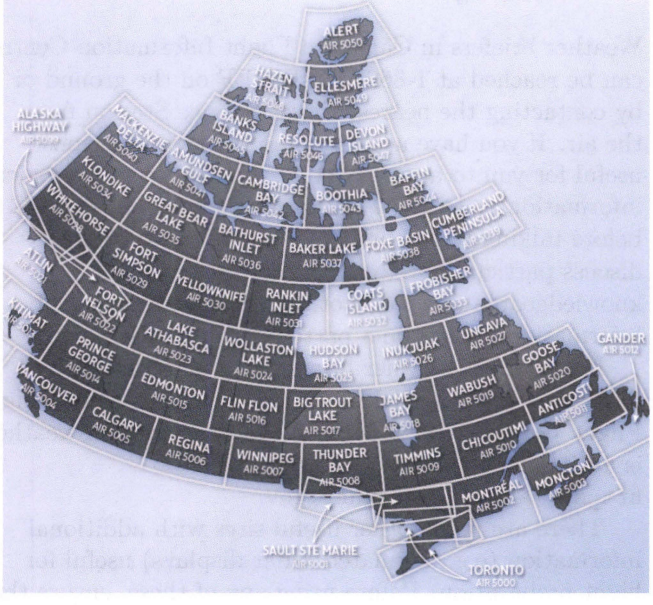

Figure 6.8: VNCs over Canada

Their scale is 1:500,000 and their projection is conical. As a rule of thumb (literally), for a rough estimate of distance, the last joint of a human thumb is about 7 nm on a VNC.

When printed on paper, VNCs are physically different maps from VTAs. When using a digital flight planning application, a VNC will automatically transform into a VTA as you zoom into one of the areas covered by a VTA.

World Aeronautical Chart (WAC)

Until 23rd September 2010, NAV CANADA produced WACs at a scale of 1:1,000,000 for the whole of Canada. The FAA in the USA stopped issuing WACs on 17th September 2015. Although many countries, such as Australia, still produce WACs, they are no longer available for North America.

Given a scale twice as large as that of a VNC (1:500,000), a WAC covered four times the area of an equivalently-sized VNC and was useful for medium performance aircraft and planning for longer cross-countries.

Enroute Low Altitude Chart (LO-Chart)

LO-Charts are primarily designed for the *en route* portion of IFR flights at altitudes below 18,000 ft ASL. They are, however, very useful for both IFR and VFR flying as they show the radio navigation aids very clearly and contain pre-calculated distances and tracks, removing the need for the pilot to draw lines and measure angles and distances. Each LO-Chart is to scale, but scales differ from chart to chart.

This section can only provide a short introduction to the symbols on a LO-chart: you should study the legend of the LO-Chart to ensure that you are familiar with all of the symbols.

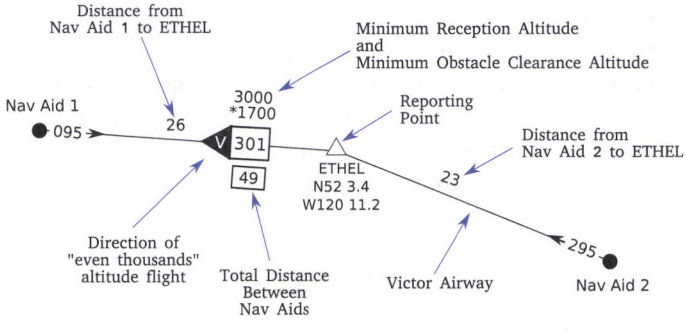

Figure 6.9: An Airway on a LO-Chart

The primary information regarding airways shown on a LO-Chart is illustrated in figure 6.9. Along a route, the primary symbols are as follows:

- The total distance between navigation aids, represented in nautical miles by a number in a box (49 = 26 + 23 in figure 6.9).
- The direction of flight at even altitudes (+500 for VFR). This is indicated by the arrow-head containing the letter V (for "victor airway"). Normally this corresponds to a westerly track, but not always.
- The Minimum Reception Altitude (MRA) for navigation aids and ATC (indicated in feet above sea level: 3,000 ft in figure 6.9).

- the Minimum Obstacle Clearance Altitude (MOCA) on the track between airways given in feet above sea level preceded by a star (1,700 ft in figure 6.9). When the MOCA is higher than the MRA no MOCA is given.

Aerodromes are also illustrated on a LO-Chart; see figure 6.10. The airport symbol itself indicates that this is a land (rather than water) aerodrome that is suitable for civil (rather than military) traffic. The symbols beneath it indicate that it lies at 199 ft ASL, that it has ARCAL lighting and that its longest runway is hard-surfaced and 9,000 ft long.

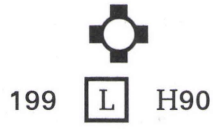

Figure 6.10: An Aerodrome on a LO-Chart

6.3.3 Checking Dates on Charts

Before using any aeronautical chart, ensure that it is up-to-date. Paper VTAs and VNCs do not have their expiry dates printed on them and it is necessary to visit the *Aeronautical Information Products* section of NAV CANADA's website to check which version of a chart is current. Paper LO charts, in contrast, have their expiry date (and time!) clearly marked. Generally, pilots fly with the charts on a tablet computer. In this case the pilot has the responsibility for ensuring that the downloaded chart is up-to-date.

6.3.4 Topographical Symbols

An explanation of the topographical symbols used on the various charts is printed on the charts themselves. Study these in detail.

6.3.5 Aeronautical Information

The different charts (VNC, VTA, LO-chart) contain a wealth of aeronautical information. In particular, note that on the VNC:

- Basic information is given about airports: whether customs service is available, their elevation, the maximum runway length and type of lighting.
- The boundaries of the different classes of airspace (particularly Classes C, D and F) are defined.
- Information regarding air to ground communications frequencies (including Remote Communications Outlets (RCOs) and Dialled RCOs (DRCOs)) can be found.

6.4 Collecting Information

Section 602.71 of the CARs states that:

> The pilot-in-command of an aircraft shall, before commencing a flight, be familiar with the available information that is appropriate to the intended flight.

This section lists some of the sources of information.

6.4.1 Weather

An understanding of the weather that will be met *en route* is obviously crucial and is called out in the CARs in paragraph 602.72:

> The pilot-in-command of an aircraft shall, before commencing a flight, be familiar with the available weather information that is appropriate to the intended flight.

Weather briefers in Canadian Flight Information Centres can be reached at 1-866-WX-BRIEF on the ground or by contacting the nearest Flight Service Station from the air. If you have access to the Internet, it is most useful for you to access NAV CANADA's meteorological information at `https://plan.navcanada.ca/wxrecall` before talking to the briefer. This will allow you to discuss particular issues with the briefer in a knowledgeable way—do not be a passive receptor of information, rather be a participant in a discussion.

In the USA, weather briefing can be obtained by dialling 1-800-WX-BRIEF on the ground or contacting Flight Watch at 122.0 MHz in the air. Aviation weather is available on the Internet at `https://aviationweather.gov`.

There are many other useful sites with additional information (e.g., animated radar displays) useful for flight preparation. Before using any of these, ensure that you are aware of the limitations of each type of display.

For more details about collecting and interpreting weather information, see chapter 5.

6.4.2 RAIM Prediction

If navigation is to be by using GPS, and particularly if GPS is to be used in the approach at the destination airport, then a Receiver Autonomous Integrity Monitoring (RAIM) prediction should be part of the flight preparation—see section 7.3.6.

6.4.3 NOTAM

A NOTAM is a *"notice containing information concerning the establishment, condition or change in any*

aeronautical facility, service, procedure or hazard, the timely knowledge of which is essential to personnel concerned with flight operations."

The precise list of conditions for which a NOTAM is issued is given in NAV CANADA's *Canadian NOTAM Operating Procedures* which is freely available online. Included are runway closures, failures of aerodrome lighting systems, unavailability of fuel, planned firework displays and significant changes in volcanic activity.

A NOTAM may be one of several types:

1. A new NOTAM, indicated by the term NOTAMN.
2. A NOTAM that replaces another, indicated by the term NOTAMR.
3. A NOTAM that cancels another, indicated by the term NOTAMC.

The format of a NOTAM that reports a runway surface condition and the Canadian Runway Friction Index (CRFI) is described in section 11.8.1 on page 251.

NOTAMs can be accessed from the NAV CANADA website at

`https://plan.navcanada.ca/wxrecall/`

This site allows you to request NOTAMs (in French, English, or both) relevant to a particular radius around an aerodrome or navigation aid (e.g., *"all NOTAMs relevant for 10 nm around CYTZ"*) or relevant within a particular distance of a route of flight (e.g., *"all NOTAMs relevant to an area 25 nm either side of a flight from CYUL to CYQB"*).

Weather reports and forecasts can be obtained from the same website.

Each section of a NOTAM is identified by a letter as listed in figure 6.11. The Q) section is not displayed on the NAV CANADA website, but it is very useful because it includes information useful for scanning NOTAMs: whether the NOTAM is of interest to VFR traffic, IFR traffic or both, and the flight levels between which the NOTAM applies. As this information is in machine-readable format, it can be used by a program to scan NOTAMs and select the ones relevant for a particular flight.

Apart from the Q) section, the other sections are displayed, when appropriate, on the NAV CANADA website. For example, the NOTAM

```
(H4205/24 NOTAMR H4030/24
A) CYOW B) 2411301303 C) 2501252359
E) OTTAWA NDB OW 236KHZ UNMONITORED)
```

contains:

A) A location: CYOW, Ottawa International Airport

B) The time the NOTAM comes into force: 13:03Z on 30th November 2024

C) The time the NOTAM expires: 23:59Z on 25th January 2025

E) The text of the NOTAM: The Ottawa NDB is not monitored

The A) section is allowed to contain only letters and some Canadian aerodomes have digits in their identifier: for example, Lachute aerodrome in Québec is CSE4. In this case the A) section references the imaginary aerodrome CXXX, and the real identifier is included in the E) section. For example:

```
(K3206/23 NOTAMR K2041/23
A) CXXX B) 2310162140 C) 2401162100EST
E) CSE4 LACHUTE
TRAINING FLT 24HR PPR 514-312-6925)
```

One part of the NOTAM that can be confusing is the acronym used when an expiry time is not exact: this is indicated by putting `EST` (estimated) after the date/time. EST does not mean Eastern Standard Time. This can be seen in the following NOTAM where it is estimated that the mobile crane will be removed by 18:00Z on 4th November 2024.

```
(E6929/24 NOTAMR E5021/24
A) CYUL B) 2410041302 C) 2411041800EST
E) MOBILE CRANE WITHIN 125FT RADIUS CENTRED ON
452719N 0734459W APRX 2080FT BFR THR 06R AND
980FT NW EXTENDED RCL. 66FT AGL 167FT
AMSL. LGTD, NOT PAINTED.)
```

This NOTAM will expire at 18:00Z on 4th November 2024. If there is a delay and the crane is still present at that time, a replacement NOTAM will have to be issued before that time.

Exercise 46 *Interpret the following NOTAM:*

```
(I7149/24 NOTAMR I6159/24
A) CBBC B) 2412311821 C) 2501311800EST
E) FUEL 100LL NOT AVBL)
```

6.4.4 Choice of Route

Even for VFR flying, the LO-charts are probably the most convenient charts to use for flight planning because they have their expiry date clearly printed on the cover; their routes avoid restricted airspace; they have the distances and bearings pre-calculated; the frequencies of navigation aids are clearly marked, and they are much less cluttered than the VNCs. One drawback of the LO-charts is that they may not indicate large bodies of

Section	Meaning	Notes
A)	Location	Aerodrome or FIRs
B)	The time the NOTAM comes into force	All times are Zulu (UTC)
C)	The time the NOTAM expires	"PERM" if it is permanent
D)	Schedule	If the NOTAM is for part of the period. E.g., "1700-2230 DLY"
E)	NOTAM text	The reason for issuing the NOTAM
F)	Lower vertical limit	If appropriate
G)	Upper vertical limit	If appropriate
Q)	Summary of the NOTAM	In machine-readable form

Figure 6.11: Sections of a NOTAM

water with sufficient clarity. When selecting a route over water, don't forget the rules that govern flying over bodies of water; see section 14.6.4 on page 318.

It can be argued that following airways as depicted on a LO-chart means a longer journey than flying direct, but often this additional distance is very small. Consider a flight from Québec City (CYQB) to Gaspé (CYGP). The great circle distance (the shortest distance on the surface of the earth) is 304 nm and the distance along airways is 318 nm, an increase in distance of just under 5% (or 8 minutes flying at 100 knots).

Another counter-intuitive method of planning the route of a flight is illustrated in figure 6.12. When planning a flight from Departville to Destville it might be better to use route 2 to the south of the low pressure to ensure that you have tailwind all the way. This trick was used by Hugo Eckener, commander of the LZ-126 airship flying from Germany to the USA in October 1924. When the airship reached the Azores it met a strong south-west wind and it was calculated that the remainder of the flight would take 70 hours, but the airship only had fuel for 50. Eckener accessed weather information from two ships and realised that, by flying north, he could use the winds around a low pressure area off Newfoundland. He therefore flew a much greater distance but managed to obtain a ground speed of over 80 knots by making use of the tailwind.

As an example, assume that the great circle distance (route 1) from Departville to Destville in figure 6.12 is 300 nm. To maintain a tailwind to Destville, you aim at a point 50 nm south of the great circle route on route 2. The increase in distance is only 16.2 nm and, at a cruise speed of 115 knot, if this route can turn a 3 knot headwind into a 3 knot tailwind, you will complete the journey in the same amount of time. If, as is likely, the wind is stronger, then you will gain time. The principle here is to plan the diversion early enough, preferably on the ground before departure.

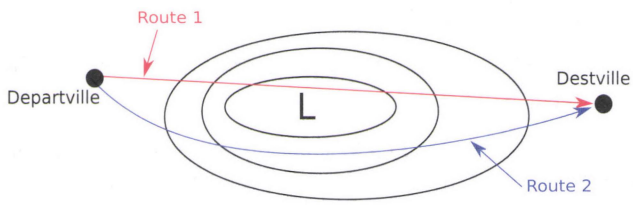

Figure 6.12: Flight Planning Around a Low Pressure Area

6.4.5 Critical Flight Points

There are two points in a flight that you need to be able to calculate:

1. The *Point of No Return.* This is the point beyond which, given the state of the winds, the aircraft has insufficient fuel to return to the departure aerodrome. Unless there are other airports where you can land, you must be sure that you will be able to land at your destination before passing this point.

2. The *Point of Equal Return* or *Critical Point.* This is the point at which, given the state of the winds, the aircraft will take exactly the same time to return to the departure aerodrome as reach its destination. If a problem occurs once you are past this point then it will be quicker to continue to your destination than to turn around and return to your departure point.

If you have a mathematical background, then these are easy to calculate without recourse to remembered formulæ. If not, then you will need to remember the following formulæ.

$$\text{pnr} = \frac{T \times v_1 \times v_2}{v_1 + v_2} \tag{6.1}$$

$$\text{per} = \frac{D \times v_2}{v_1 + v_2} \tag{6.2}$$

where:

- pnr is the distance of the Point of no Return from the departure point.

- per is the distance of the Point of Equal Return from the departure point.
- T is the number of hours of fuel in the aircraft's tanks at departure.
- v_1 is the ground speed of the aircraft when flying to the destination.
- v_2 is the ground speed of the aircraft when flying back to the point of departure.
- D is the total distance from the point of departure to the destination in nautical miles.

Exercise 47 *You are to fly an aircraft in northern Canada between two points 400 nm apart. The track to be flown is* 045° *true and the anticipated wind is from* 090° *true at 20 knots. The aircraft flies with an airspeed of 105 knots and, at departure, has enough fuel for 5.5 hours flying. Calculate the critical points for this flight.*

Exam Hint 15 *In an examination it is very easy to check your calculation for the point of equal return. Simply calculate the time for the return trip and the time for the continued trip and confirm that they are equal (1 hour 55 minutes in exercise 47).*

6.4.6 Fuel Requirements

A full description of the fuel requirements for VFR and IFR flights is given in section 14.6.6 on page 320. In summary, for a VFR flight, *taking into account all anticipated delays,* it is necessary to have sufficient fuel to reach the destination airport and then continue cruise flight for 30 minutes during the day or 45 minutes at night. Note the emphasis on anticipating delays. These might arise from:

- pre-takeoff delays (waiting for other aircraft to depart)
- ATC rerouting
- weather-related delays
- in a multi-engined aircraft, the loss of any engine
- in a pressurised aircraft, the loss of cabin pressure and the necessity to fly at a lower altitude
- delays on arrival. At some airports, such as Montréal's Pierre Elliott Trudeau, arriving at a peak time, such as early evening on a weekday, will almost always result in delays in getting a landing clearance—the pilot must anticipate this.

6.4.7 Weight & Balance

Calculating an accurate weight and balance at takeoff (and for some aircraft, at landing) is essential for a safe flight. The technique to be employed is described in section 11.6 on page 247.

6.4.8 Canada Flight Supplement

In addition to the obvious listing of aerodromes with their runways and radio frequencies, the Canada Flight Supplement is full of useful information.

The following parts of a paper copy of the CFS are often overlooked:

- The format of a VFR position report. It is good practice to give a position report to a Flight Service Station approximately every 45 minutes when flying cross-country and not in contact with a Flight Following service. The format for the report is on the back cover of paper copies of the CFS and should be followed. For example:

  Pilot: London Radio, Foxtrot Papa Tango November with a position report.

  London Radio: Papa Tango November, go ahead.

  Pilot: Foxtrot Papa Tango November was at 44 degrees 15 minutes north, 77 degrees 48 minutes west at 12:34 Zulu, near Peterborough, 6500 feet, VFR to Toronto City Centre.

  London Radio: We copy that, Papa Tango November. Current Peterborough altimeter setting is 29.45.

  Pilot: Papa Tango November.

  Note that, as a time is given in the position report, it is not necessary to transmit the report immediately. Note also that a latitude and longitude (from a GPS or map) is the most precise way of giving the position but it is also common to use a navigation aid (e.g., "over YOW"). If you give a position with latitude and longitude then it can help the flight service representative if you also name a nearby airport. This allows him or her to give you the local altimeter setting without having to consult a map.

- The format of a pilot report (PIREP). Flight Information Centres rely on pilots to report on

weather conditions which are either better or worse than those forecast. The format of a PIREP is also on the back cover of paper copies of the CFS. For more information about interpreting and providing PIREPs, see section 5.3.4 on page 100.

- The format of a flight plan. This is also given on the back cover of paper CFSs.
- Hazards to Aircraft Operations. There are numerous military areas not marked on the VFR charts that are often active. It is important for any pilot on a cross-country flight to be aware of these. They are listed by province in section C of the CFS.

6.4.9 Mandatory Documents

There are several documents that *must* be carried on board an aircraft during flight. These are listed in section 11.1.5 on page 231.

Note that the aircraft's technical logs (airframe, fuselage, engine, propeller) should *not* be carried on board an aircraft in flight. It is also inadvisable to carry your personal logbook in the aircraft.

6.4.10 Aircraft Serviceability

Before you fly an aircraft you must ensure that it is serviceable. In particular, check the aircraft logs to ensure that:

- an annual inspection (or equivalent for commercially-registered aircraft) has been carried out within the last 12 months.
- the emergency locator transmitter (ELT) has been certified within the last 12 months.
- the compass has been swung within the last 12 months. The compass must also be reswung if the aircraft has been struck by lightning or if any new equipment has been added to the aircraft.
- if the aircraft is to be flown IFR or VFR in transponder airspace, a pitot-static check and recertification of the altimeter has been carried out in the past two years.

6.5 Flight Plans/Itineraries

A flight plan and flight itinerary both contain the same basic information about a flight: point of departure, destination, route, colour of aircraft, amount of fuel on board, pilot's name, number of souls on board, etc.

A flight plan must always be filed for international flights. Otherwise a flight plan or flight itinerary must be filed for any flight going over 25 nautical miles from the departure aerodrome. If the flight enters the Air Defence Identification Zone (ADIZ)—see section 14.6.10 on page 323—then the flight plan or flight itinerary must be filed with ATC, an FSS or a community aerodrome radio station. Otherwise a flight itinerary may be filed with any responsible person.

A domestic VFR flight plan may include an intermediate stop if the stop is expected to be short (e.g., to take on fuel or allow a passenger to board). In this case the stop time in hours and minutes is included in the route section. For example, a 30 minute stop at Winnipeg International would be entered as

```
...CYWG 0030 CYWG ...
```

Anecdote 19 *I feel that recording the time of an intermediate stop can put pressure on the pilot to take off again on schedule. Personally, I would always file two flight plans.*

6.6 Answers to Exercises

This section contains possible answers to the examples in this chapter.

Exercise 42

The sun takes 1 hour to travel every 15° of longitude. It will therefore take

$$\frac{114°\ 14'}{15} = \frac{114.233°}{15} = 7.62 \text{ hours} = 7 \text{ hrs } 37 \text{ mins}$$

for it to reach Rimbey from Greenwich. The local time in Rimbey will therefore be 7 hours 37 minutes earlier than Greenwich, i.e., 04:57.

Exercise 43

Following the red line on figure 6.3, it can be seen that, on 20th April at 50° N, morning civil twilight will begin at 04:00 local time (not Zulu time and not time zone time: the sun does not understand time zones).

Exercise 44

This is an interesting question. Clearly it is related to the equinox, the date when the number of hours of daylight and darkness are the same at all locations. This is confirmed by the beginning of the twilight shown in figure 6.3 being at 06:00 local time. However, the equinox occurs around the 20th March and 22nd September each year, and figure 6.3 indicates that the times where all the lines cross

are about 10th March and 5th October: each about two weeks different from the equinox. When questioning astronomers about this, the answers tend to be "unconvincing".

Exercise 45

Firstly calculate the correct local time. As the longitude is 77°46′ west, the local time will be

$$\frac{77°\ 46'}{15} = \frac{77.77°}{15} = 5.18 \text{ hrs} = 5 \text{ hours } 11 \text{ mins}$$

behind Zulu time. The local time is therefore 14:23 - 05:11 = 09:12.

Consulting the table given in figure 6.4 on page 119 under the column for 09:12 and the row for "JUN 29", we find that the sun's true bearing is 117.5°.

We therefore point the aircraft at the sun and set the heading indicator to 117.5°, remembering that this is a true rather than magnetic bearing.

Exercise 46

This is a replacement NOTAM (NOTAMR), replacing NOTAM I6159/24. It relates to the CBBC (Bella Bella, British Columbia) aerodrome and states that, from 18:21Z on 31st December 2024 until 18:00Z on 31st January 2025, 100LL fuel is not available. The end date is an estimate (EST) and a new NOTAM will be issued either cancelling this one (NOTAMC, if fuel comes available) or replacing this one (NOTAMR, if fuel is still not available by the end of January).

Exercise 47

The values to be used in equations 6.1 and 6.2 are as follows:

- $T = 5.5$
- $v_1 = 89.9$ (calculated using a triangle of velocities: see appendix F)
- $v_2 = 118.2$ (calculated using a triangle of velocities: see appendix F)
- $D = 400$

Substituting these values into the equations gives:

$$\begin{aligned} \text{pnr} &= \frac{5.5 \times 89.9 \times 118.2}{89.9 + 118.2} = 280.8 \\ \text{per} &= \frac{400 \times 118.2}{89.9 + 118.2} = 227.2 \end{aligned}$$

Thus, if the winds are as forecast, you will not be able to return to your departure point once you are more than 280.8 nm into the journey. When you are 227.2 nm into the journey, your time to return to your point of departure will be the same as the time to continue to your destination (1 hour 55 minutes).

Chapter 7

In-Flight Navigation

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As an introduction to the various types of navigation, this chapter outlines the concept of "Performance-Based Navigation". It then covers what radio waves are and how they propagate through space and then moves its focus to today's most common navigation method, whether in cars or aircraft: navigation by means of transmissions from satellites. Navigation using ground-based radio transmitters is covered in section 7.4 and subsequent sections.

7.1 Performance-Based Navigation (PBN)

In the past, whether or not an aircraft was permitted to navigate a particular route based on radio navigation aids was specified by the presence or absence of particular pieces of equipment on board: for example a victor airway between VORs could only be flown by an aircraft having a VOR receiver. With the advent of new types of navigation systems, this reliance on particular pieces of equipment is becoming outdated.

Anecdote 20 *Some years ago I was departing one of the airports in Washington DC, USA and, as with the other departing IFR traffic, I was cleared to fly directly to a VOR in the north of the city. That VOR was actually not operational, but this was not preventing the departing aircraft flying directly to it, using satellite navigation.*

"Performance-Based Navigation" specifies how accurately an aircraft needs to be able to navigate to be allowed into a particular piece of airspace. If it can be demonstrated that the aircraft can navigate sufficiently accurately, then it is irrelevant whether that is through satellite navigation or by reference to ground stations. For example, an IFR approach plate might state that a VOR receiver and DME are required to fly a particular approach. In the future, it is expected that this equipment list would be replaced by a requirement that the aircraft be able to navigate (by whatever means) with a particular accuracy.

The definition of "sufficiently accurately" comprises five factors:

1. **Accuracy:** Can the navigation system determine the position of the aircraft within a specified distance of its actual position 95% of the time? This should not be confused with point 3 below: the accuracy requirement is that, *if the system provides a position,* then it should be sufficiently accurate 95% of the time. Requirement 3 deals with the proportion of the time that the system *will* provide a position.

2. **Integrity:** What confidence can be placed in the information from the navigation system? Here it is particularly important that, if the system can no longer meet its accuracy requirements, it warns the pilot in a timely manner. For GPS navigation this warning could be provided by RAIM; see section 7.3.6.

3. **Availability:** For what percentage of time is the navigation system able to perform its function?

4. **Continuity:** Can the system continue to provide a sufficiently accurate service without interruption?

5. **Functionality:** What functions can the system actually perform?

The intent is to improve airspace capacity (more aircraft can be allowed into a piece of airspace if it is known that they can navigate with a particular accuracy) while not reducing safety.

There are also operational efficiencies. Today, if there were an operational need to move a VOR, then dozens of airways, arrival procedures and possibly instrument approaches would need to be changed. With PBN, waypoints can be moved dynamically as operational conditions (weather, traffic volumes, etc.) change. This makes for a much more efficient use of the available airspace, particularly around large airports.

Increasingly, routes will be labelled by their Required Navigation Performance (RNP) level. For example, RNP 2 requires the use of certified GNSS receivers with RAIM fault detection, whereas at RNP 4 aircraft must have at least two fully-serviceable, operational and independent long range navigation systems listed in the flight manual.

Currently, the only way of complying with the various RNPs is by means of GNSS or certified Inertial Navigation Systems. However, it is anticipated that, in the future, there may be other suitable technologies and, by specifying an RNP rather than a required equipment list, Transport Canada (and ICAO) is effectively saying, "You must have the necessary equipment to navigate as accurately as *this* in *this* type of airspace. The equipment that you use to do that is your affair."

A full description of the PBN standards can be found in ICAO's *Performance Based Navigation Manual* which is available from the ICAO online store.

7.2 Radio Theory

7.2.1 Radio Waves

Radio signals travel in waves and the obvious question is "what is it that is moving in a wave?" With water waves we can clearly see the surface of the water moving, but what is the equivalent with radio waves? The answer is that radio waves are actually two waves at right angles to each other, one wave being in the strength of an electrical field, the other in the strength of a magnetic field; see figure 7.1 where the electrical field is labelled **E** and the magnetic one **B**. The waves in figure 7.1 are travelling in the **x** direction.

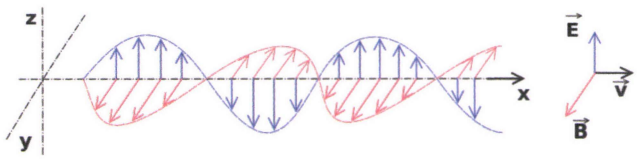

Figure 7.1: A Radio Wave (SuperManu, CC BY-SA 3.0)

Because they have these two components, radio waves are called electromagnetic waves. They belong to the same family as heat (infrared), X-rays and visible light, differing only in the length of the waves—see figure 7.2.

Figure 7.3 illustrates three of the key concepts of radio waves (drawn, for simplicity, as a single wave).

1. **Speed.** The speed of any electromagnetic wave in a vacuum is exactly 299,792,458 metres per second. This is a definition, not a measurement—a metre is defined to be the distance light travels in a vacuum in 1/299,792,458th of a second.

2. **Wavelength.** The distance between two peaks of the wave measured in metres. As can be seen from figure 7.2, radio waves have wavelengths of between 20 cm and 10 metres while visible light has a much smaller wavelength.

3. **Amplitude.** The magnitude of the signal measured in volts per metre. This is a measure of the power of the radio signal. AM (Amplitude-Modulated) radio stations change the amplitude of the transmitted signal to convey the speech.

There is a fourth key concept, that of **frequency.** This can be expressed in terms of the speed and wavelength.

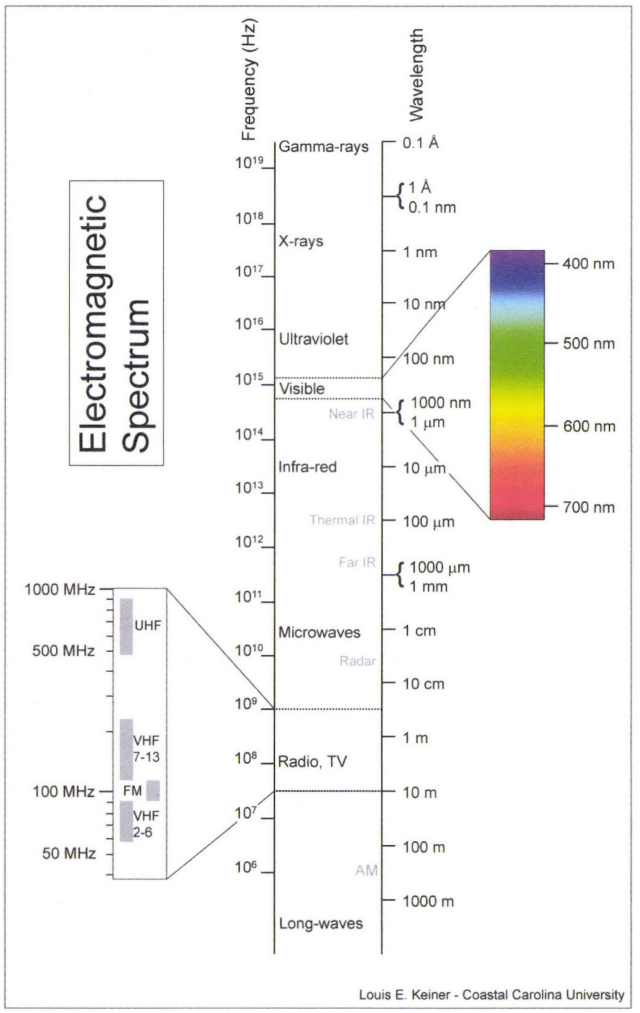

Figure 7.2: The Electromagnetic Spectrum (Louis E Keiner)

Imagine watching a radio wave (as shown in figure 7.3) going past and counting the peaks as they pass by. The number of peaks that pass in a second is called the *frequency* of the wave. If 1,000 peaks pass every second then the wave is said to have a frequency of 1 kHz (kiloHertz). If 1,000,000 peaks pass in a second then the wave is said to have a frequency of 1 MHz (MegaHertz). FM (Frequency-Modulated) radio stations change the frequency of the transmitted signal to convey the sound or picture.

Observe that Hz must always have a capital H since it is named after Heinrich Hertz.[1]

As the speed of electromagnetic waves is constant, it is clear that if you are given the frequency of a radio wave it is possible to calculate its wavelength: the greater the number of peaks that pass every second, the shorter the wavelength must be.

[1]Sometimes one sees the unit mHz (milliHertz). This is the frequency at which 1,000 seconds elapse between peaks.

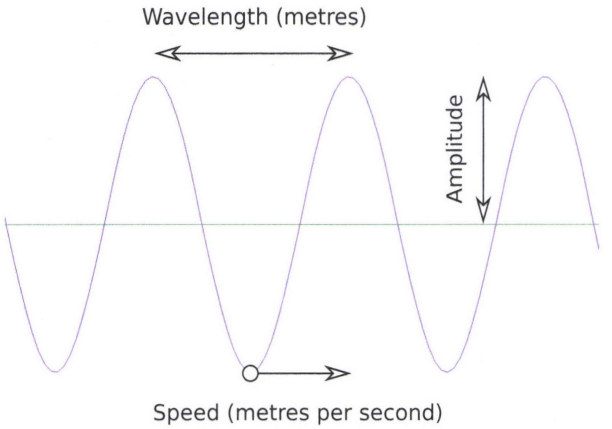

Figure 7.3: Characteristics of a Radio Wave

Exercise 48 *What is the wavelength of the radio waves transmitted by the Ottawa VOR (114.6 MHz)?*

Answers to exercises in this chapter are included in section 7.9 starting on page 148.

7.2.2 Frequency Bands

Radio waves are classified according to their frequencies as shown in figure 7.4. The Frequency Bands used for aviation are listed in figure 7.5.

Low Frequency and Very Low Frequency signals are able to follow the surface of the earth (the so-called *Ground Wave* phenomenon) while higher frequency signals must generally be line-of-sight between the transmitter and receiver.

The approximate maximum line-of-sight distance from a transmitter to a receiver is given by:

$$\text{distance} \approx 1.23 \times \sqrt{\text{height}_1 + \text{height}_2} \qquad (7.1)$$

where *distance* is in nautical miles and height_1 is the height in feet of the transmitter above the surrounding terrain and height_2 is the height of the aircraft above the terrain.

Exercise 49 *You are flying at 6,500 ft ASL over an area where the mean terrain height is 1,000 ft ASL. At what approximate range can you receive a VORTAC on a ridge 935 ft above the surrounding terrain?*

Description	Frequencies	Notes
Very Low Frequency	3-30 kHz	Can penetrate water and so are used to communicate with submarines near the surface
Low Frequency	30-300 kHz	Used in many countries for time signals and also used for LORAN
Medium Frequency	300-3000 kHz	Used for NDBs
High Frequency	3-30 MHz	Sometimes called "short-wave"
Very High Frequency (VHF)	30-300 MHz	VORs and voice communication
Ultra High Frequency (UHF)	300-3000 MHz	Television signals, GPS signals and microwave ovens

Figure 7.4: Classification of Radio Waves

Anecdote 21 *The VOR receiver in my aircraft automatically transcribes the Morse code identifier and displays the three-letter result on the screen. This means that I don't have to listen to the Morse code myself to confirm that I have correctly tuned the VOR. I have found, however, that I can distinguish the Morse code from the background noise about 20 miles further away from the VOR transmitter than the automatic system can—there are still some things that humans are better at than computers.*

In addition to line-of-sight and ground wave propagation, there are two other ways for radio waves to propagate:

1. Skywave propagation, also called "skip", is caused by refraction in the ionosphere. The ionosphere is affected by the sun on a daily cycle and the 11-year sunspot cycle determines how much refraction occurs. During solar cycle minima, when there are few sunspots, frequencies up to approximately 15 MHz are refracted but during solar maxima, when there are many sunspots, the whole HF range up to 30 MHz can be used for long-distance communication.

2. Tropospheric scattering can affect VHF and higher frequencies by scattering the signals back from a height of approximately 6 miles (10 km). When this occurs, over-the-horizon communications can take place using VHF.

7.3 Global Navigation Satellite System

Global Navigation Satellite System (GNSS) is a generic term for navigation systems using timing signals from satellites to determine position. Various countries have launched, or are in the process of launching, GNSS systems: the USA's *Global Positioning System* (GPS), Russia's *GLONASS*, the European Union's *Galileo* and China's *Beidou* system. India's NavIC and Japan's QZSS (Quasi-Zenith Satellite System) are regional systems. The remainder of this section describes the GPS system, but much of the description is common to the other GNSSs.

Frequency Range	Use
190-535 kHz	NDBs in North America
108-112 MHz	Localisers
108.1-117.95 MHz	VORs
118-136 MHz	Voice Communications
329-335 MHz	Glideslopes
1575.42 & 1227.6 MHz	GPS

Figure 7.5: Frequencies used in Aviation

7.3.1 Principles of Operation

Outline

The GPS system is based on a number of satellites broadcasting orbital information and time signals twice a minute based on their local clock: on the minute and at 30 seconds past the minute. The clocks in the different satellites are accurate to within 30ns (nano-seconds: one thousandth of a millionth of a second).

When there are sufficient satellites above the horizon, and they are reasonably well distributed across the sky, a GPS receiver can compare the signals from the different satellites and use triangulation to determine its position. When the time according to the satellite's on-board clock is, say, 12:00:30, it will broadcast a message starting with that time. If a receiver gets a signal from satellite A saying that its time is 12:00:30 shortly before it receives a signal from satellite B saying that its time is 12:00:30, then it knows that it is closer to satellite A and by how much. Doing this comparison

for the signals from four satellites, and knowing where the satellites are in their orbits at that time, the receiver can calculate its position in three-dimensional space.

More Details of Operation

The description given above is adequate for the Transport Canada examination. More background details are given in this section.

More than 70 GPS satellites have been launched and, although some have failed, the intention is to keep at least 24 satellites operational at any time. These satellites are travelling in predictable orbits about 20,200 km above the ground. They are *not* in geostationary orbit; rather they travel at about 14,000 km/hr relative to the earth and, if you look at the sky on a dark night just after the sun has set, you can often see them moving quite quickly and smoothly across the sky. They complete an orbit around the earth roughly every 12 hours.

All of the GPS satellites broadcast on the same frequencies (see figure 7.5) and at the same time according to their local clocks. This poses the question of how the receiver can distinguish between the signals from different satellites. The answer is that each satellite uses a different pseudo-random bit sequence (zeros and ones) to encode its signal. The receiver has to be aware of the different pseudo-random codes in order to be able to decode a signal from a particular satellite.

The 1,500 bit data frame that each satellite transmits has three parts, as illustrated in figure 7.6:

1. The current date and time and a measure of the health of the satellite. The date and time are encoded as the week number and seconds into the week starting at 00:00:00Z on 6th January 1980.

2. The "ephemeris" defining the satellite's precise orbit.

3. The "almanac" information describing the position of other satellites in the constellation. Twenty-five successive frames are needed to transmit all of the constellation data.

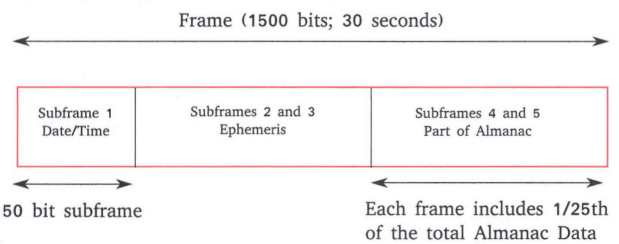

Figure 7.6: A GPS Frame

These signals are transmitted at 50 bits per second and so each frame takes 30 seconds to transmit. The transmission occurs on the minute and half-minute according to the satellite's on-board clock. A complete signal consists of twenty-five frames comprising 37,500 bits. This takes $12\frac{1}{2}$ minutes to send at 50 bits/second.

Normally, when it is first switched on, a GPS receiver in an aircraft is able to calculate its position more quickly than this, based on a knowledge of its position when it was switched off and its last-received almanac information.

The receiver saves the transmitted time and spacial coordinates from each satellite, as well as its own clock time at which the signal was received. The receiver's own clock will be much less accurate than the clocks in the satellites, but as long as the satellites are all synchronised, the inaccuracy (bias) in the receiver's clock will be the same for all satellites. The receiver can then assemble simultaneous equations in the three spacial variables and the bias in its clock. To solve equations with four variables, at least four equations are needed, and so transmissions must be received from at least four satellites. If signals are being received from more than four satellites, then the solution is "over-determined" and a more accurate position can be calculated.

The actual algorithm used is complex and involves General Relativity.[2] Because the satellites are moving quickly, the relativistic effects cause their on-board clocks to gain about 38 microseconds per day over earth-based clocks. This has to be taken into account when a position is calculated.

7.3.2 Differential GPS

When four satellites are in view, the receiver can calculate its position (latitude, longitude and height) to within about 10 metres. When more satellites are in view, then this error can be reduced, but *differential GPS* can be used to improve accuracy further. This involves a number of base stations situated on the ground whose positions are known very accurately. These base stations receive the same signals from the GPS satellites as aircraft do, but since their positions are known, corrections can be calculated. These corrections are then transmitted to the moving receivers on each suitably equipped aircraft and applied to correct the aircraft's position.

There are two differential GPS systems: the wide-area augmentation system (WAAS) and the ground-based augmentation system (GBAS). In North America, GBAS used to be called the local-area

[2] This is one of the two devices on board a general-aviation aircraft that makes use of the principles of General Relativity. Can you identify the other?

augmentation system (LAAS) and, although it has been defined, it has never been widely deployed.

- WAAS consists of 38 ground reference stations (in 2024) positioned across the United States, Mexico, Puerto Rico and Canada (in Winnipeg, Goose Bay, Gander and Iqaluit) that monitor GPS signals. The error data are sent by the reference stations to three master stations, where a consolidated correction is calculated. The correction is made available to the GPS receiver in the aircraft by broadcasting it through one of three geostationary satellites.

- GBAS operates in a similar manner to WAAS but was designed to provide even more accurate position information in the local area around an airport. This would allow GPS approaches to be designed with more precision and therefore lower minima.[3] The intention is that eventually it will be possible to have full Category III approaches (i.e., autoland with no visibility). GBAS uses four base stations located close to the airport which receive signals from the satellites and calculate local errors. The errors are then transmitted on a VHF radio channel to aircraft in the neighbourhood. A single GBAS system could offer significant cost savings at airports with multiple runways—several ILS installations on different runways could be replaced by a single GBAS system.

WAAS and GBAS also solve another problem inherent in the use of GPS for instrument approaches—the detection of faults in the transmitters. An ILS, for example, is monitored and if it fails, aircraft can be warned almost immediately. The GPS satellites, on the other hand, do not generally provide this type of detection: if a satellite becomes faulty and starts transmitting bad clock signals, then that would not normally be easily detected by the GPS receiver. Within the WAAS and GBAS systems such a failure *is* detected and the appropriate information is passed to the receivers in the aircraft.

7.3.3 Aircraft Equipment

There are many different GPS receivers available, ranging from hand-helds for VFR use (see, for example, figure 7.7) to panel-mounted receivers for IFR operation. It is one of the weaknesses of GPS that every GPS receiver has a different mode of operation. In general, any pilot faced with a new VOR receiver would know how to use it almost immediately. A pilot faced with a new GPS receiver may need a great deal of training and practice. Most manufacturers provide computer-based simulators for their IFR GPS products and any pilot thinking of using one is well advised to complete a number of simulation sessions before using it in actual flight, particularly in IMC.

Figure 7.7: A VFR GPS Receiver: the Garmin Aera 660

A GPS receiver can be expected to have the following components:

- A receiver, with a built-in or separate antenna, capable of receiving the signals from a number of satellites and computing its position.

- A database of airports, navigation aids, reporting points, airspace and other information. For accurate navigation it is necessary to ensure that this database is kept up-to-date—it is not that airports and navigation aids move, but that some entries in the database are inaccurate and need updating, and radio frequencies change. The GPS manufacturer handles these with database updates.

- A map display (e.g., figure 7.7) showing the position of the receiver relative to nearby airports, navigation aids and airspace. If a route has been set, then there will be a line on the map indicating where the aircraft is, relative to the direct route to the destination. Typically the map can be configured to be "north-up" or "track-up". In normal use, the "track-up" mode is probably the easier to use as the desired track is then displayed as a vertical line.

- An HSI-type display indicating the current track (not heading!) of the aircraft and its position relative to the direct track to destination (see section 7.5 for a description of an HSI). Most receivers also have a "glideslope" line on the HSI display indicating the descent profile needed to arrive at the destination airport at circuit height.

[3]The term "minima" refers to the lowest altitude to which an aircraft flying an instrument approach may descend without the runway being in sight. Typically for an ILS this is 200 ft AGL.

- A numerical display including the track (not heading) and ground speed (not airspeed) being flown, and the time and distance to destination. When the aircraft is approaching a waypoint, the display will lead the pilot into the turn: "Turn right to 130 in 9 seconds...".

Although they are not part of the GPS functionality, many receivers accept weather information and the position of nearby aircraft (e.g., from an ADS-B receiver) and display these on the moving map.

A pilot typically needs to configure various parameters before using a GPS receiver in flight, including the following:

- Choice of units (km/hr or knots, nautical miles or kilometres, etc.).
- Choice of the amount of "clutter" to be displayed on the map screen.
- Choice of map datum: the reference point from which measurements are made. The most commonly used datum is the North American Datum 1983 (NAD83).
- Minimum requirements for an airport to be chosen as a "nearest airport" in an emergency (e.g., hard-surfaced runway of at least 1,500 ft).
- Specification of the alerts that should be issued when approaching different types of airspace.
- Specification of the distances from terrain or obstacles at which warnings should be given.

In addition to the basic GPS functions listed above, a GPS receiver certified for IFR approaches will also have a database of approaches, and VFR units often have "E6B-type" calculators to allow wind speed and direction to be determined, given airspeed and heading.

7.3.4 Tuning & Identifying

Tuning is not required because the GPS satellites broadcast on fixed frequencies—see figure 7.5.

7.3.5 Interpretation

When using a GPS for navigation, many pilots only use a single feature of their GPS receivers: "Go Directly To". When a route consists of several legs and extensive rerouting by ATC is not anticipated, it can be useful to enter the full route before the flight and allow the GPS to step through it automatically, alerting you of upcoming turns.

Once a waypoint has been entered, navigation is as simple as following the line on the moving map or keeping the deviation bar on the HSI display centred. One word of warning: entering, for example, CYOW, YOW or OW as your destination will take you to three different places (the Ottawa Airport, the Ottawa VOR or the Ottawa NDB). Make sure that you have correctly chosen the destination to which you want to fly. This can be particularly important in the USA where the initial letter (K) of airport identifiers tends to be dropped, creating a confusion, for example, between KART (the Watertown airport) and ART (the Watertown VOR). Some GPS receivers want you to enter "airport/ART" or "VOR/ART" while others want you to enter KART or ART. Be careful.

Remember that the bearing given on the GPS display is a track across the ground, not the heading of the aircraft. This can create a dilemma if, for example, ATC gives you the instruction to "turn left to 230". Strictly speaking this is a heading that the controller has already adjusted for wind—you should therefore fly a *heading* of 230°. In practice, many controllers seem to prefer you to fly the track that they have given you. If there is a strong crosswind and you are in doubt, *ask* the controller.

One situation where knowing your track can be very useful is when tracking a VOR radial. Once you have the VOR's CDI needle centred, there is no need to experiment to find a crab angle that will keep you on the radial—simply fly the correct track and note the heading. Keep that heading with an occasional glance at the GPS.

Exercise 50 *You are east of the Brandon VOR and have received the instruction "Fly heading 045 to intercept the 085 radial of the Brandon VOR and fly outbound. Maintain 3,500 ft." Explain how you could use your hand-held GPS to help fly this accurately.*

Most GPS receivers allow the user to specify a particular track from any point on the ground (including, for example, a VOR). Thus, given the instruction "Fly heading 040 to intercept the 085 radial from the North Bay VOR and fly outbound" it should be simple to use the GPS to draw the 085° radial from the VOR on the moving map. As a pilot, you can then fly the 040° heading until you reach the line and fly along it.

Although it is an option to be used only in an emergency when all else has failed, drawing a line on the runway heading from an aerodrome may help you to find a runway in poor visibility. Note however that the latitude and longitude of the aerodrome in the GPS database may not be on the runway and by using the GPS you may be lining up on the terminal building.

7.3.6 Inaccuracies/Limitations

The book *Uncertainties in GPS Positioning: A Mathematical Discourse* by Alan Oxley[4] provides a very thorough, although somewhat mathematical, discussion on the inaccuracies in GNSS systems (although the title refers to GPS, it also covers GLONASS and Galileo).

RAIM Errors

The GPS satellites do not internally check their operation, and major errors of calculated position can occur if one or more of the satellites starts to broadcast slightly incorrect timing information. To protect against this, some GPS receivers are fitted with Receiver Autonomous Integrity Monitoring (RAIM).

RAIM makes use of information from more than the required minimum number of satellites to cross-check the satellites against each other. To allow RAIM to work, there must be sufficient satellites visible to the receiver and those satellites must be distributed across the sky—not clustered too closely together. If you are intending to use GPS as a primary means of navigation at your destination, then you must obtain a RAIM prediction for your flight to determine whether there will be enough visible satellites for RAIM to work when you arrive. There are numerous programs available for this on the Internet and any Flight Service can also provide the information. You can ask "If I arrive at Victoria at 19:34Z tomorrow will there be sufficient GPS satellites visible to satisfy RAIM?" IFR certified GPSs switch themselves off if a RAIM error occurs in flight so it is important to have a RAIM prediction before taking off. The RAIM prediction only takes into account the anticipated positions of the GPS satellites and the scheduled maintenance on them. It does not take into account any unscheduled satellite failures.

Database Errors

Another source of error is incorrect information in the GPS's database. For example, in the database available for many GPS receivers at the time the first edition of this book was being written, the position of Rolph airport (on the Ottawa River in Ontario) was several miles away from its real position. The pilot is responsible for ensuring that the waypoint's position is correct in the database and, for this purpose, the latitude and longitude of reporting points are given on LO-charts; see figure 7.8 where the latitude and longitude of QW and WILKY are given.

GPS databases need to be updated every 28 days for IFR flying, but there are no requirements for updates for VFR navigation. An out-of-date database is another possible source of errors.

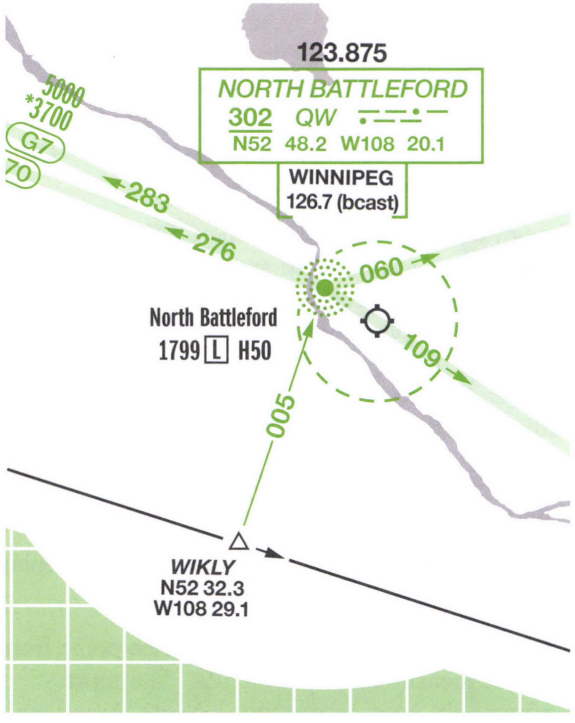

Figure 7.8: A Waypoint (WILKY) with Location

Multipath Errors

A multipath error occurs when the signals from a GPS satellite are reflected by a building before being received and processed. This can also occur when GPS repeaters are installed to improve the signal reception in a built-up area. Such reflections are unlikely to affect an aircraft at altitude in cruise flight, but could affect navigation during an approach into an airport within a city.

Propagation Errors

There are many other, smaller errors that are largely corrected by differential GPS. These include the slowing of the radio signals from the satellites as they pass through the charged particles of the ionosphere and then through the water vapour in the troposphere. This makes the clock appear to be running slowly, interfering with the calculation of position. Ionospherical delays are one of the reasons why GPS satellites broadcast on two frequencies: measuring the relative delay of the same signals on the different frequencies allows the ionospheric delay to be estimated and its effect eliminated from the calculation.

[4]ISBN 978-0-12-809594-2

Spoofing & Jamming Interference

Since GPS signals are very weak when they arrive at receivers, it is easy for other sources of electromagnetic radiation to overpower them, making acquiring and tracking the satellite signals difficult or impossible. Solar flares can cause this—see the section on the Carrington Event below—but GPS signals can also be interfered with by naturally occurring geomagnetic storms mainly found near the north and south poles, and by deliberate or accidental human-generated interference.

In April 2001, the entire harbour at Moss Landing, California, USA, was unable to receive GPS signals due to unintentional jamming caused by a malfunctioning TV preamplifier. Short-range GPS jammers are available for as little as C$16 on Amazon.

Spoofing, rather than jamming, a GPS signal is harder and there is a mechanism within the GPS protocol to prevent it happening. However, very few, if any, civilian GPS receivers implement the mechanism. On 4th December 2011, a USA drone was captured by Iranian forces near the city of Kashmar in Iran, apparently by signals being sent to it to spoof GPS satellite signals. By tricking the drone into believing that it was in Afghanistan, the Iranians brought the drone in to land with minimum damage.

On 7th August 7th 2015, Yang Qing and Huang Lin demonstrated a $1,000 GPS spoofing system at the DEFCON security conference in Las Vegas, USA. Since then, the cost of these devices has dropped to under $300.

At the USENIX Security Symposium in 2018 a group of researchers from Virginia Tech, USA, the University of Electronic Science and Technology of China and Microsoft Research published a paper[5] describing how they had subtly spoofed the GPS signals to highjack a car. As their paper says:

> GPS spoofing attacks have two key steps: First, in the takeover step, the attacker lures the victim's GPS receiver to migrate from the legitimate signal to the spoofing signal. The takeover phase can be either brute-forced or smooth. In the former case, a spoofer simply transmits the false signals at a high power, causing the victim to lose track of the satellites and lock on to the stronger spoofing signals. In contrast, smooth takeover begins by transmitting signals synchronized with the original ones, and then gradually overpowering the original signal to cause the migration. The advantage of smooth takeover is the stealthiness, since it will not generate abnormal jumps in the received signal strength.

[5] Available at `https://www.microsoft.com/en-us/research/uploads/prod/2018/06/security18gps.pdf`

The device used for the spoofing operated only at short range, but it was capable of taking over the navigation features of a car in such a smooth way that 95% of the drivers in the experiment did not notice the attack: they simply drove to the wrong destination. The whole device cost US$223.

Access Denial

The GPS system is operated by the US Department of Defense and, although it is required by law to "maintain a Standard Positioning Service ... that will be available on a continuous, worldwide basis", it is also permitted to deny access to the system, or to degrade its accuracy, if that would be in the USA's national interest. This degredation happened in 1999 during the Kargil conflict between India and Pakistan and could, in principle, happen at any time.

Carrington Events

On 1st September 1859, two British astronomers, Richard Carrington and Richard Hodgson, observed a coronal mass ejection from the sun (solar flare). This travelled at 8,523,000 km/hr directly toward Earth and caused significant disruption when it arrived. Auroras were seen as far south as the Caribbean. In the Rocky Mountains the glow woke gold miners, who began preparing breakfast because they thought it was morning. People in Boston, USA were able to read a newspaper by the aurora's light.

Of more relevance to today's GPS system, telegraph systems all over Europe and North America (the "Internet of the day") failed, in some cases giving telegraph operators electric shocks. Telegraph lines threw sparks and some telegraph operators could continue to send and receive messages despite having disconnected their power supplies.

If a solar storm of this type could damage relatively robust telegraph wires, it could also destroy delicate satellites. In 2003, a solar storm of much less intensity than the Carrington Event caused interruptions of service from 47 satellites, including one that was destroyed. WAAS in North America went offline for more than a day.

In 2013, Lloyds of London and the Atmospheric and Environmental Research, Inc. produced a report entitled *"Solar Storm Risk to the North American Electric Grid"* which indicates that "historical records of solar events suggest that a reasonable range for the average return period for an extreme geomagnetic storm is 100-250 years."

In 2015, the UK Government produced a report entitled *"Space Weather Preparedness Strategy"* which estimates that "a reoccurrence of the Carrington Event

has a 1% annual probability" and the advance warning that we will get could be under twelve hours—less than the duration of some long-haul flights.

Both of these reports are freely available on the Internet.

With more and more systems, both in aviation and on the ground, relying on GPS, we need to be conscious of this threat.

For all of these reasons, *GPS should not be relied upon as the sole means of navigation.*

7.4 VHF Omnidirectional Range

7.4.1 Terminology

In addition to the term *VOR*, the terms *VORTAC* and *TACAN* are sometimes used with regard to VOR transmitters. A TACAN (TACtical Air Navigation transmitter) is a VOR-like device colocated with a DME transmitter (see section 7.8) transmitting signals for military aircraft. A VORTAC is a VOR colocated with a TACAN.

The symbols for a VOR, a VORTAC and a VOR colocated with a DME differ on a LO chart but, for the purposes of civilian navigation the differences can be ignored.

There is also a terminology difference between types of VOR: conventional VORs and Doppler VORs (DVORs). The primary difference between these types is mentioned briefly below but is not important to the pilot: a VOR receiver works with either.

7.4.2 Principles of Operation

A VOR transmitter on the ground (see figure 7.9) transmits a VHF radio signal which is amplitude-modulated by two 30 Hz signals. In a conventional VOR, one of the 30 Hz signals is used to modulate the frequency of a signal 9960 Hz below the VOR's published frequency.[6] This signal is broadcast in all directions and forms a reference signal.

The second signal is used to modulate the amplitude of the carrier and is broadcast with a phase shift dependent on the direction from the VOR: see figure 7.10. Thus, if an aircraft is east of the VOR (on the 90° radial) it will receive two 30 Hz modulations: one lagging the other by 90°. Similarly, if the aircraft is southwest of the VOR (on the 225° radial), it will receive the two signals 225° out of phase.

Figure 7.9: A VOR (Alison Hobbs)

In a Doppler VOR, the carrier is amplitude modulated by the reference signal and frequency modulated by the variable signal: i.e., the types of modulation are reversed. This provides a signal that is more immune to reflections from nearby buildings than a conventional VOR.

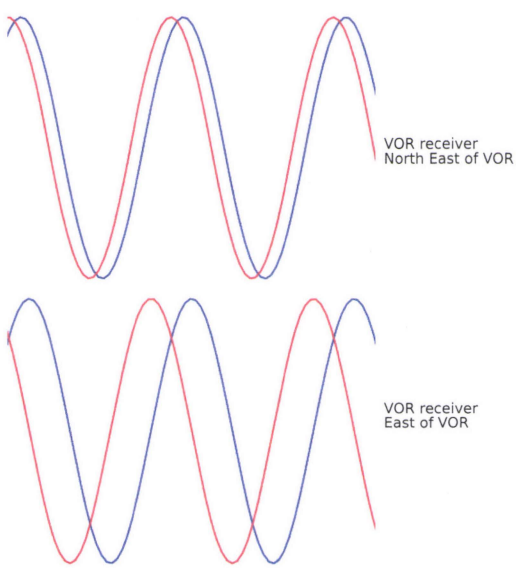

Figure 7.10: Signals from a VOR

By comparing the phase (relative delay) of the two 30 Hz signals, the receiver can determine and display the aircraft's position relative to the VOR.

Note that the amplitude of the reference signal is also modulated to provide the Morse Code or other identifier of the VOR.

[6] i.e., the frequency of the 9960 Hz sub carrier changes at 30 Hz.

VOR transmitters are continuously monitored for correct operation and shut down automatically if the transmitted signal goes outside preset limits. The limits differ between countries, but are typically around 1° for DVORs and better than 4° for conventional VORs.

7.4.3 Aircraft Equipment

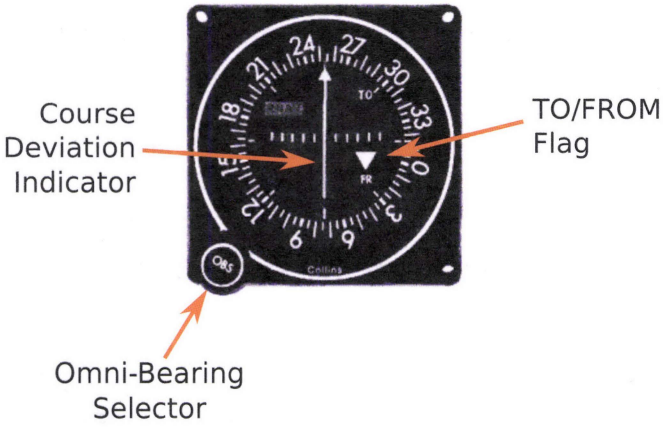

Figure 7.11: A VOR Display

A receiver is required in an aircraft to receive and process VOR signals (this receiver is, confusingly, also called a VOR). Often this receiver also acts as a localiser and glideslope receiver. The display is illustrated in figure 7.11 and typically consists of:

- a circular dial with bearings displayed around it which can be turned using a so-called *omni-bearing selector* (OBS). In figure 7.11 the OBS has been turned to place 254° at the top.
- an indicator displaying one of the three conditions: TO, FROM or OFF. This indicator takes different forms on equipment from different manufacturers: sometimes it is an arrow pointing upwards, downwards or switched off. Sometimes it is the actual displayed word. In figure 7.11 it is a triangle pointing downwards and the letters *FR* indicating *FROM*.
- a needle, known as a *course deviation indicator* (CDI), that can deflect to the left or right of the vertical. In figure 7.11 it is centred.

If the receiver can also display glide-slope information then it will also have a needle that can be deflected above or below the horizontal.

7.4.4 Tuning & Identifying

Before a VOR is used for navigation it must be positively identified. Most VORs transmit their identity in Morse Code and some receivers are able to decode this signal and display the identity without the pilot's involvement. If this feature is not available on the receiver then it is the pilot's duty to listen to the audio signal from the VOR and confirm that it is transmitting the expected identity. Some VORs also transmit local weather or SIGMET information in addition to the Morse code identifier. In some places in the USA, the VOR frequency is actually used for transmitting ATC information to a pilot—the pilot cannot tune the VHF radio to transmit on a VOR frequency, but can tune the VOR receiver to listen.

If the VOR receiver is to be used to receive a glideslope signal then there is no need to tune this as tuning and identifying the associated localiser will automatically set the correct frequency for the glideslope.

7.4.5 Serviceability Check

The accuracy of a VOR receiver should, if possible, be checked before use. There are several ways of doing this:

Using a VOR Checkpoint. A number of aerodromes have VOR checkpoint signs located beside taxiways. These signs indicate a point where there is sufficient signal strength from a nearby VOR to check the aircraft's receiver. Use the OBS to centre the CDI needle and check that the bearing at the top of the display is within 4° of the bearing indicated on the sign.

Using two VORs. If the aircraft is equipped with two VOR receivers that have only an antenna in common then they may be checked by tuning them both to the same VOR and centring the needles. Do this with a TO and then with a FROM flag. In each case the bearing at the top of the VOR displays may not differ by more than 4°.

Ground feature check. If no other method of checking is available then the aircraft should be flown over an obvious ground feature which lies directly below a published radial from a VOR. The receiver should be tuned to the VOR and the displayed bearing must differ by not more than 6° from the bearing of the published radial. Note that only published radials (those with victor airways) from the VOR can be used for this since the accuracy of non-published radials from a VOR is not guaranteed.

It is also possible to calibrate the VOR against an **IFR-certified GPS** although it is not clear whether this is a legal method of ensuring the accuracy of the VOR.

It used to be possible to test a VOR by using VOR Test Facilities (VOTs) which were located at various airports. These were phased out in Canada during 2009, but still exist in the USA. If the airport has a VOT then it can be used as follows. Tune the VOT frequency and check the identity of the transmitter is a series of Morse Code dots. Turn the OBS to centre the CDI needle with a FROM flag. The bearing at the top of the VOR display should be between 356° and 004°. If it is, turn the OBS to centre the CDI needle with a TO flag. This time the bearing at the top of the display should be between 176° and 184°. If either of these checks fail then the VOR must not be used for IFR navigation.

7.4.6 Interpretation

The VOR display was designed at a time when electronics was complex and was made easy for the receiver to display, even at the cost of complexity in its interpretation.

Consider the VOR shown in figure 7.12. This display should be read as follows:

1. The FROM flag tells you that if you were to fly a *track* (not heading) of 280°, you would be flying away *from* the VOR. Note that this flag tells you nothing about whether you are, in fact, flying towards or away from the VOR—the VOR receiver knows nothing about your heading.

2. The needle being to the left of centre tells you that if you were to fly a *track* of 280°, you would have to turn left to intercept a line drawn from 100° to 280° through the VOR. The needle tells you nothing about whether you should turn left or right to get to the VOR or to intercept a particular radial from the VOR—the VOR receiver knows nothing about your heading.

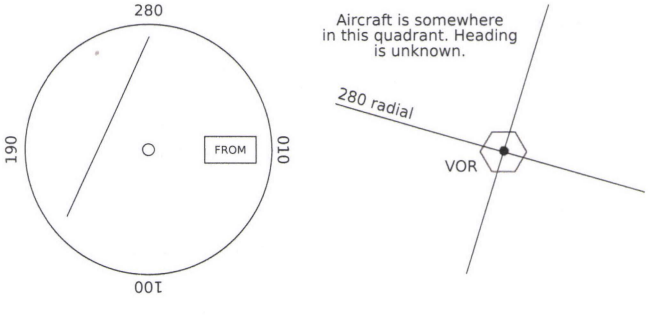

Figure 7.12: VOR Display

The TO/FROM flag can also display an OFF value. This indicates, as shown in figure 7.13, that flying the heading set on the VOR receiver would take you neither to nor from the VOR.

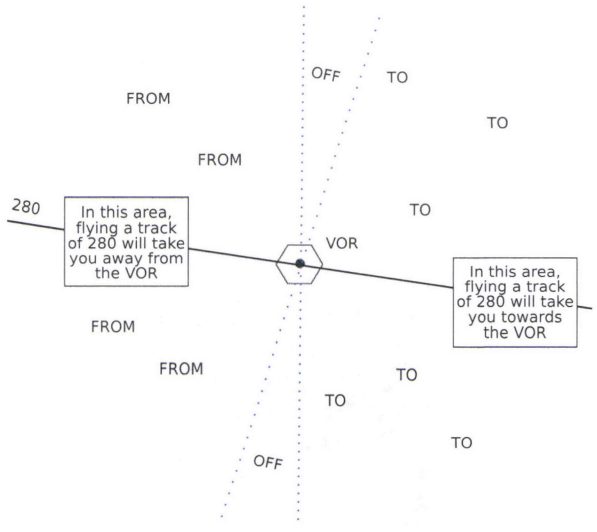

Figure 7.13: VOR TO/FROM Flag with OBS set to 280°

Exercise 51 *Consider the VOR in figure 7.11. What information can be determined from this display about the position of the aircraft?*

Homing to a VOR is very simple:

1. Tune and identify the VOR.

2. Turn the OBS until the CDI needle is centred and the flag indicates TO. As described above, the bearing at the top of the VOR display now gives you the *track* to fly in order to go directly to the VOR.

3. Turn to the indicated track. If you can determine your track from a GPS, you simply need to fly this to maintain a centred VOR needle. If you do not have a GPS, then fly a heading which will give you approximately the correct track. As the needle moves to the left or right make a suitable correction by turning towards the needle and flying until it centres and then turning back towards your original heading. Repeat this until you find a heading that gives you the correct track to keep the needle centred.

When the VOR receiver is used in localiser[7] mode (by tuning a localiser—there is typically no switch between these modes) turning the OBS has no effect on the position of the CDI needle.

7.4.7 Intercepting Radials & Tracking

The procedure to intercept a predetermined radial and fly outbound or inbound to a VOR is straightforward:

[7] A localiser is a signal transmitted to indicate the runway centre line on some instrument approaches.

1. Tune and identify the VOR.
2. Use the OBS to set the inbound or outbound track at the top of your VOR display. Note that, if you are to fly inbound then the track you will be flying will be the reciprocal of the radial you are tracking (e.g., to fly the 270° radial inbound you will be flying 090°).
3. Check that the VOR needle deflects in the direction you expect. If not, then your situational awareness is inadequate and you are likely to fly in the wrong direction for the intercept.
4. Select a suitable heading (or track if you have a GPS available) to fly in order to intercept. The angle you choose will depend on the speed of your aircraft and your position relative to the VOR. If you are close to the VOR and need to fly inbound (see figure 7.14), then an intercept angle of 90° may be needed to ensure that you intercept before reaching the VOR. If you are further from the VOR or are intending to track outbound then a 45° interception is better.
5. As the VOR needle centres, turn onto the correct inbound or outbound track. If you have a GPS then fly the required track. Otherwise, fly the heading and as the VOR needle moves off centre, make the appropriate heading correction.

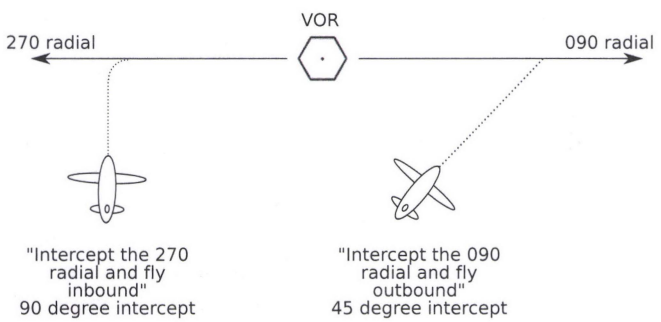

Figure 7.14: Intercepting a VOR Radial

Exercise 52 *You are south east of the Grindstone VOR and are given the instruction "Intercept the* 100° *radial from the Grindstone VOR and track it outbound." What action would you take?*

7.4.8 Position Lines & Fixes

If two VOR transmitters are in range of your receiver, finding your precise position is easy:

1. Tune and identify the first VOR.
2. Centre the VOR's CDI needle with a FROM flag showing.
3. Note the bearing at the top of the VOR. This is a bearing that would take you directly away from the VOR. Draw a line on your map from the centre of the VOR at the given bearing. You are somewhere along this line.
4. Tune and identify the second VOR.
5. Centre the VOR's CDI needle with a FROM flag showing.
6. Note the bearing at the top of the VOR. Draw a line on your map from the centre of the VOR at the given bearing. You are at the point where the two lines intersect.

When using this technique, try to select VOR transmitters where the two bearing lines intersect as close as possible to a right angle. This will reduce the error in your position.

See also the *Position Lines & Fixes* for NDBs in section 7.6.7. The two techniques can, of course, be combined if there is one NDB and one VOR in range.

7.4.9 Time & Distance Formula

The scenario below assumes the following:

- you need to determine how long it will take you to reach the VOR towards which you are flying
- there is no wind
- you have neither DME nor GPS on board
- you are willing to fly out of your way to find out.

The technique is best illustrated by an example.

Assume that you are flying inbound on the 025° radial to a VOR and wish to determine the time it will take you to reach the VOR.

First, select a radial close to the one on which you are already flying, say the 020° radial, and turn to a track at right angles to this chosen radial. (It is not clear how you fly a particular track, rather than heading, but, if you have a GPS, this should be easy. Of course, if you have a GPS you would not be carrying out this manoeuvre.) In this example, the track at right angles to 020° is 290°. Turn the OBS on the VOR to 020° and turn right to a track of 290°.

Note the time when the VOR's CDI needle centres (say 12:03:00). At this time you are on the 020° radial flying at right angles to it. Rotate the OBS to 010° and

again wait until the CDI needle centres and note the time (say 12:05:04). You are now on the 010° radial and flying almost at right angles to it.

Perform the following calculation:

$$\frac{\text{Time in secs between radials}}{\text{Difference in radials}} = \frac{124}{10} = 12.4$$

The result is the time in minutes required to fly to the VOR once the inbound track is regained. In this case it will take approximately 12 minutes 24 seconds to reach the VOR.

In addition to the foregoing example, consider exercise 53 as an alternative to any that may be set on a Transport Canada examination. Doing the exercise will ensure that you are familiar with triangles of velocities (see page 353).

Exercise 53 *You are flying directly towards a VOR in the southern domestic airspace, westbound on the* 090° *radial with an airspeed of 100 knots. You are actually 30 nm from the VOR, and the wind is blowing from* 290° *M at 30 knots, but you don't know this. You decide to turn right* 90° *and measure the time it takes you to reach the* 080° *radial to determine the time it will take you to reach the VOR. Compare the actual flight time with that estimated by the time and distance formula.*

7.4.10 VHF Airways & Routes

Airways and Air Routes are routes between navigation devices. They are most clearly seen on LO charts but are also marked on VNCs. Such routes are characterised by:

1. the type of radio beacons or other navigation aids at each end of the route:
   - If the route lies between two positions identifiable only by the use of GPS, it is designated by a "Tango" number of the form T371. Increasingly, other forms of routes are being replaced by Tango routes as NDBs and VORs are being decommisioned.
   - If the route lies between VORs then it is termed a VHF airway or air route and is normally designated by a "Victor" number of the form V123. Note that the number following the V gives no indication of the track—it is simply a sequence number to identify the airway or air route.
   - If the route lies between two NDBs it is termed an MF (Medium Frequency) airway or air route and is designated by a letter other than V or Q (e.g., BR33, R2).
   - If the route lies between, for example, a VOR and an NDB, then it is normally considered to be an MF airway or air route although this is not always the case: e.g., V367 between the Sioux Lookout NDB (YXL) and the International Falls VOR (INL).
2. the type of airspace through which the route passes. If it lies in uncontrolled airspace then it is known as an air route. If it lies in controlled airspace, then it is known as an airway.

Exam Hint 16 *Many students believe that the difference between an airway and an air route is that airways are between VORs while air routes are between NDBs. This is not the case: whether a path is an airway or air route is determined only by the type of airspace through which it passes.*

Airways start vertically 1,200 ft AGL and have a width of 8 nm out to 51 nm from the navigation devices; air routes start at ground level and have no defined width.

7.5 Horizontal Situation Indicator

A horizontal situation indicator (HSI) is both a flight and a navigation instrument. By displaying both flight and navigation information in one place, it reduces the pilot workload.

HSIs have recently become popular because even the simplest hand-held aviation GPSs display a so-called HSI page with many even offering a "glideslope" for descent to a destination airport. This is not a genuine HSI because the GPS cannot display aircraft heading, only track, but it is in many respects more useful than a genuine HSI. The remainder of this section describes a genuine HSI, but you should be able to transfer the information to your GPS's "HSI" without problem.

HSIs are also common instruments in "glass cockpits".

A mechanical HSI is typically a vacuum driven gyroscopic instrument (although electrical models also exist) normally mounted below the attitude indicator—replacing the heading indicator. The HSI can be thought of as a heading indicator and VOR/Localiser/Glideslope receiver combined in one unit. This means that an instrument pilot, can navigate and fly instrument approaches using just the "six-pack" of instruments without having to interrupt the scan to look at localiser and glideslope displays elsewhere.

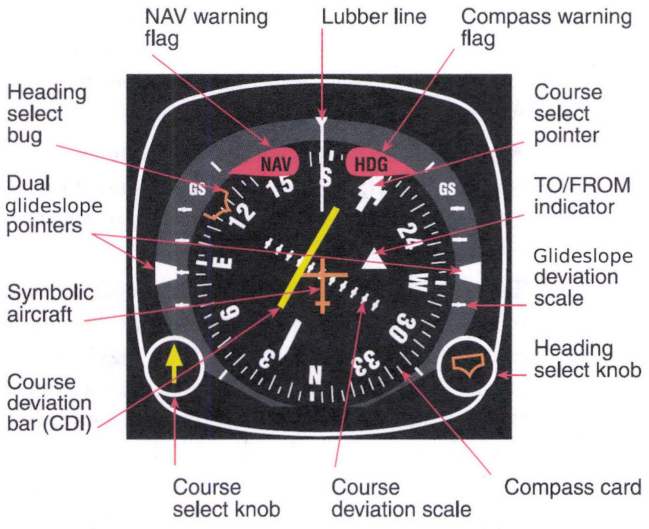

Figure 7.15: An HSI Display

The HSI also removes one of the most confusing aspects of instrument flight: interpreting whether to turn left or right to intersect a course to a VOR or a localiser front or back course. The HSI handles any reverse sensing needed and always correctly indicates a turn to the left or right, thereby reducing the pilot's workload. In figure 7.15, for example, the aircraft is currently to the right of the desired track (see the picture of the aircraft relative to the course deviation bar).

The HSI contains the following components:

- A heading indicator slaved to a magnetic flux gate (as in an RMI) meaning that, unlike a heading indicator, it does not need to be reset periodically against the compass. Like many heading indicators, it is possible to move a "heading bug" to indicate a desired heading: this acts as an *aide-mémoire* for the pilot. In figure 7.15 it has been set to about 116°. If the HSI is coupled to an autopilot, then the autopilot will track the heading indicated by the bug.

- A course selection pointer. This is set to indicate the course that the aircraft should be flying: for example, to track a VOR radial or localiser. In figure 7.15, for example, the course has been set to about 200°.

- A course deviation bar (sometimes called the lateral deviation or D-bar) indicating whether the aircraft is to the right or left of the desired course. In figure 7.15, for example, the aircraft is to the right of the desired track as indicated by the lateral deviation bar. This differs from a CDI needle on a VOR because a VOR has no knowledge of the aircraft's heading and cannot therefore indicate whether a left or right turn is required to intercept a desired track.

- A lubber line indicating the aircraft's current heading. In figure 7.15, the aircraft is heading at 176°. The lower tip of the lubber line can be used to intercept the desired track smoothly: if heading is adjusted to keep it at the top of the course deviation bar, the aircraft will make a clean intercept. In figure 7.15, for example, the aircraft needs to make a heading correction to the right to bring the lubber line and course deviation bar into contact.

- An aircraft symbol. This, combined with the course deviation bar, represents the current position of the aircraft relative to the required course.

- A TO/FROM flag, as in a VOR display.

- A course reciprocal pointer at the bottom of the device that mechanically does the arithmetic of adding or subtracting 180° to the desired course. This is helpful if you are told to fly a particular VOR radial inbound as it is easier to set the radial on the course reciprocal pointer than perform the necessary mental arithmetic.

Most HSIs also include a glideslope display, thus providing vertical as well as horizontal situational awareness and giving the lie to the name of *Horizontal* Situation Indicator.

7.6 Automatic Direction Finder

7.6.1 Principles of Operation

An ADF in an aircraft can be used to detect Medium Frequency (see figure 7.4) radio transmissions and point a needle towards their transmitter. Typically the radio transmissions would be commercial AM radio stations or Non-Directional Beacons (NDBs). NDB navigation is more important in the north of Canada and the NDBs installed there tend to be of either medium (50 to 2,000 Watts) or high (above 2,000 Watts) power. In the southern domestic airspace, many NDBs are of low power (less than 50 Watts). NDBs are being phased out and many of those that remain are being NOTAMed as "unmonitored": see the NOTAM on page 123.

In older ADFs there were two distinct antennæ:

1. A loop antenna that was rotated by hand (in which case it is not truly an *automatic* direction finder) or electrical motor to detect the strongest signal. This allowed the ADF to determine the line on which the transmitter lay, but not whether the transmitter was behind or ahead of the aircraft.

2. A sense antenna that broke the tie and determined whether the transmitter was in front of or behind the receiver. This antenna also received the identification Morse Code from the transmitter. It was often a long wire from the top of the fuselage to the tip of the vertical tail.

In a more modern receiver the antennæ are combined into a single solid-state antenna often mounted below the fuselage.

7.6.2 Aircraft Equipment

Figure 7.16: The ADF Display

The ADF consists of the following components:

- A method of tuning to the transmitter. In newer units this is a digital tuning device, in older units an analogue dial.
- A way of listening to the identification being transmitted. In the case of an NDB, this will normally be a Morse Code signal; in the case of an AM radio station it will be the programme being transmitted. In some Precision Radar Approaches (PARs) the controller's instructions to a pilot may be broadcast through a nearby NDB (see the General Pages of the *Canada Air Pilot* for details).
- A needle indicating the direction to the transmitter backed by a card marked with the compass bearings: see figure 7.16. In some units, such as that shown in figure 7.16, it is possible to rotate the card manually to bring any particular bearing to the top but, unlike a VOR receiver, moving the card does not affect the needle. This is known as a "moveable-card" as opposed to a "fixed-card" ADF.
- A multi-position switch with some or all of the following options:
  - **OFF.**
  - **ADF.** This is the position that the switch must be in for normal operation. The ADF is connected to both antennæ and operates as an ADF.
  - **Antenna.** In this position the ADF is connected only to the sense antenna. This is used when using analogue tuning to get the strongest signal.
  - **Test.** In this position the ADF needle swings to a particular position (commonly "3 o'clock" or "9 o'clock"). This test can be used to ensure that the needle is pointing to a genuine transmitter. If the needle does not swing back once the test mode is released then it is probably *not* pointing to a genuine station.
  - **BFO.** Some ADF systems have a "Beat Frequency Oscillator" (BFO) position. This is used to identify stations that transmit keyed CW (Carrier Wave) rather than amplitude modulated signals. Such stations are found in Europe, but not in North America.

7.6.3 Tuning & Identifying

Before being used for navigation the identification of the transmitter must be checked. If the transmitter is a commercial radio station then its identification will be transmitted at irregular intervals. In the case of an ADF, the Morse Code signal is transmitted continuously. Unlike a VOR receiver, there is no "flag" on an ADF, indicating that the signal from a station has been lost and, to ensure that the transmitting station has not failed, it is necessary to listen to the station's identification continuously.

7.6.4 Serviceability Check

There is no formal serviceability check for an ADF equivalent to that of a VOR (see section 7.4.5) but basic serviceability can be checked by:

- ensuring that the ADF needle is pointing in a reasonable direction. If you expect the NDB to be passing to your left then ensure that the ADF needle points to the left.
- periodically selecting TEST mode on the receiver. This causes the needle to deflect and releasing TEST should cause the needle to return briskly to its original position.

7.6.5 Interpretation

The ADF needle always points to the transmitting station. To home to an NDB it should only be necessary

to change the aircraft's heading to ensure that the ADF needle is pointing straight up. In fact, this technique will bring the aircraft to the NDB eventually, but as illustrated in figure 7.17, possibly not by the most direct route.

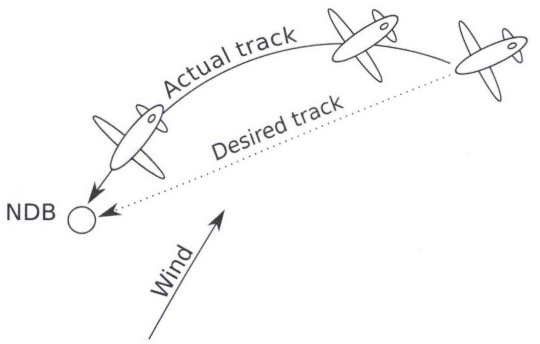

Figure 7.17: Naive NDB Tracking

To track accurately to an NDB use the following technique:

1. Tune and identify the NDB.
2. Reset the aircraft's heading indicator from the magnetic compass.
3. Turn the aircraft until the ADF needle is pointing directly upwards to indicate that the aircraft is pointing directly towards the NDB. Note the heading carefully. For the sake of example, we will assume that it is 234°.
4. If you have a GPS (even a handheld one) then find a heading to fly to maintain a track of 234°. If there is a crosswind, then the heading will be something other than 234° and the ADF needle will not be pointing directly upwards. Continue flying this track and the ADF needle should not move.
5. If you do not have a GPS then:
   - fly the noted heading precisely and note the direction that the ADF needle moves. In our example we will assume that it moves clockwise by 5°. This indicates that you have been blown south of your desired track.
   - turn right (towards the ADF needle) by twice the error, in this example turn to a heading of 244°.
   - fly until the ADF needle points 10° counter-clockwise from straight up. You have now intercepted your desired track again.
   - turn left half of the angle you turned to reintercept, in this example 5° to a heading of 239°.
   - wait to see what happens to the ADF needle. If it does not move then you have found the correct heading to fly to remain on the direct track to the NDB. If it does move, repeat the process from step 5.

Once you have determined the initial track to the NDB, you are seeking a stable situation where the difference between your heading and the direct track is the same as the difference between the position of the ADF needle and "straight up".

Tracking away from an NDB can be handled similarly, *mutatis mutandis*.

Exercise 54 *Assume that the ADF whose display is shown in figure 7.16 has been correctly tuned to the NDB and that the aircraft is flying on a heading of* 050°. *To what direction should the pilot turn the aircraft to fly directly to the NDB?*

Note that a GPS approved for IFR operation can be used in lieu of an ADF and tracking directly to or from an NDB is then very simple.

Exam Hint 17 *Tracking an NDB in a crosswind or intercepting tracks to or from an NDB is a high workload activity. In a flight test, if there are other navigation devices in the aircraft, it may be best to placard the ADF as inoperable.*

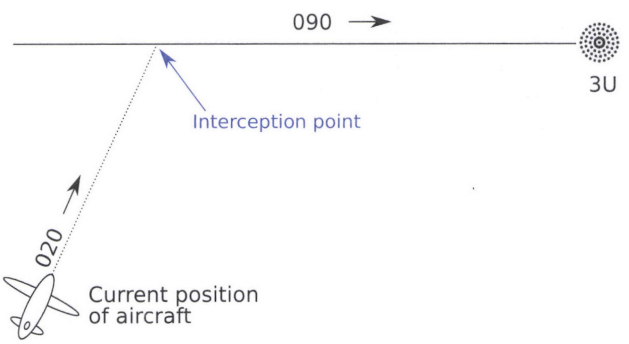

Figure 7.18: Diagram for Exercise 55

7.6.6 Intercepting Tracks

A moveable card ADF is one that has a method of turning the card behind the ADF needle. Some older ADFs have a fixed card that cannot be moved. Note that, even when the card is moveable, moving it has no effect on the position of the needle (unlike, for example, moving the card on a VOR).

The purpose in moving the card is to perform simple addition as illustrated in the exercises 54 and 55.

Exercise 55 *Consider the situation in figure 7.18 and assume that you have been given the instruction "Fly heading 020 to intercept and fly inbound to the 3U NDB on a track of 090". How will you determine the interception point where you need to turn from a heading of* 020° *to a track of* 090°*?*

7.6.7 Position Lines & Fixes

If two NDBs are in range of your receiver, finding your precise position is easy:

1. Tune and identify the first NDB.
2. Reset your heading indicator from the compass.
3. Turn the ADF card until your current heading is at the top.
4. Note the bearing shown on the ADF card *at the base* of the ADF needle. This is the bearing directly away from the NDB. Draw a line on your map at that bearing away from the NDB.
5. Tune and identify the second NDB.
6. Note the bearing shown on the ADF card *at the base* of the ADF needle. This is the bearing directly away from the NDB. Draw a line on your map at that bearing away from the NDB.
7. You are at the point where the two lines intersect.

When using this technique, try to select NDBs where the two bearing lines intersect as close as possible to a right angle. This will reduce the error in your position.

See also section 7.4.8. The two techniques can, of course, be combined if there is one NDB and one VOR in range.

7.6.8 Time & Distance Formula

The technique to find the time to fly to an NDB is exactly the same as the corresponding technique for a VOR—see section 7.4.9. The only difference is that since an NDB does not have radials, the bearing change has to be used instead.

7.6.9 Inaccuracies/Limitations

ADFs are subject to errors:

- when the aircraft is banked. Bank error is present in all turns because the loop antenna is mounted so that its axis is parallel to the normal axis of the aircraft. Bank error is particularly important during IFR NDB approaches.
- when the incoming radio waves have been reflected by the ionosphere and are returning to the earth typically 30 to 60 miles from the transmitter. This effect is most pronounced during the period just before and after sunrise and sunset. Generally, the greater the distance from the station, the greater the effect. NDB transmissions on frequencies lower than 350 kHz have very little twilight effect.
- when the aircraft is in a position where mountains or cliffs can reflect radio waves. The ADF receives the incoming signals from the wrong direction.
- when the aircraft is close to mountains containing magnetic deposits; these cause undefined indications on the ADF.
- when the aircraft is flying close to a shoreline. The shoreline can refract low frequency radio waves as they pass from land to water. If you are flying over water, you should not rely on an NDB signal that crosses over the shoreline at an angle less than 30°.
- when an electrical storm is nearby. Electrical storms generate radio waves of many frequencies, including the frequency to which the ADF may be tuned. The ADF needle will then point to the source of lightning rather than to the selected station.

7.6.10 LF/MF Airways & Routes

See section 7.4.10.

7.7 Radio Magnetic Indicator

As described above, it is sometimes convenient to turn an ADF card to place the aircraft's heading at the top of the display—see section 7.6.7 and exercise 55. It would obviously be convenient for this to be performed automatically, requiring no pilot input as the aircraft changes heading.

This effectively describes a *Radio Magnetic Indicator* (RMI): a moving card connected to a magnetic flux gate compass so that the aircraft's heading is always at the top without input from the pilot.

Superimposed on the card are one or two ADF needles and one or two VOR needles. The VOR needles

Figure 7.19: A Bendix/King KI-229 RMI

act in the same way as ADF needles but point to VOR transmitters.

The RMI shown in figure 7.19, for example, indicates that the aircraft's heading is about 326°M, the tuned NDB lies about 36° to the left of the aircraft on a track of 290°M and the VOR lies about 40° to the right on a track of 006°M. Note that although the position of the NDB is displayed on an ADF-type display, the display of the VOR's position is nothing like that of a normal VOR receiver.

7.8 Distance Measuring Equipment

Distance Measuring Equipment (DME) ground stations are indicated by square boxes on aviation charts and are often, but not always, co-located with VORs. They operate on frequencies between 962 MHz and 1212 MHz but are rarely tuned by frequency because they are paired with a VOR or localiser frequency (see *DME Frequency Pairing Plan* in section D of the CFS) and the receiver is tuned to the corresponding VOR rather than to the DME itself.

Once tuned, DME ground stations are identified by the same Morse Code as the corresponding VORs but at a lower frequency: normally once per 30 seconds.

Exercise 56 *You tune and listen to the identification Morse Code of a VOR. You find that it is only being transmitted every 30 seconds. What does this tell you about the operational status of the VOR?*

In some cases, there is no VOR colocated with the DME. One example is the DME at Havre St-Pierre, QC. The frequency associated with the DME is given as 109.3 MHz, a VOR frequency. But there is no VOR! In this case, had there been a VOR at Havre St-Pierre, its frequency would have been 109.3 MHz. By tuning the aircraft's DME unit to that frequency, it will pick up the signal from the DME ground station that is actually transmitted on 1054 MHz. The DME in the aircraft will transmit on 991 MHz.

The basic mode of operation of a DME is that the DME unit on the aircraft transmits two interrogation signals separated by a time specific to that transmitter. The ground station receiving the signal waits for $50\mu s$ and then responds using the same signal spacing but on a different frequency. By accepting only those returned signals with the correct spacing, the DME receiver can ignore signals initiated by other aircraft and, by measuring the delay and subtracting the $50\mu s$, can calculate (and display) its distance from the ground station.

Because of this method of measuring, the distance displayed is the slant distance from the aircraft to the ground station—not, as is the case with GPS—the ground distance. For the distinction between these see figure 7.20. As can be seen, the difference between GPS distance and DME distance is greatest when the aircraft is flying at a high altitude close to the ground station. An IFR-certified GPS can always be used in lieu of a DME and a distance would be reported to ATC as "15 miles" instead of "15 DME".

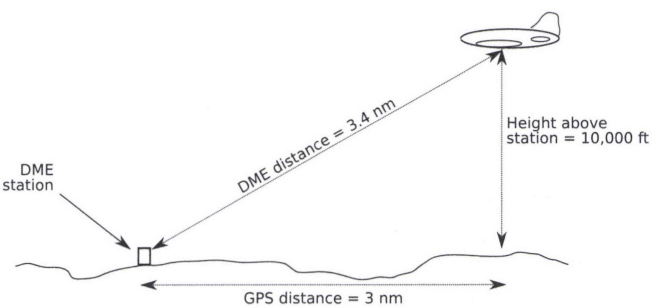

Figure 7.20: GPS and DME Distances

DME equipment has a number of limitations:

- A DME ground station can only handle signals from a pre-defined number of aircraft at a time (often 100 or 200). If more aircraft than this interrogate it at the same time, the signals from some aircraft are simply ignored. For this reason, if you are not using your DME, it is courteous to turn it off to allow other aircraft to use the ground station.
- A DME unit in an aircraft can take 10 seconds or longer to establish solid contact with the ground station and display useful values.
- The ground speed that DMEs display is based on the rate at which the distance to the ground station

is changing. This is an accurate measure of ground speed only when the aircraft is travelling directly towards or away from the DME ground station.

- The "time to station" display is a simple computation from the distance to station and computed ground speed. It is therefore only accurate when flying directly to the transmitter. When flying directly away from the transmitter it is a "time from station".

Note that, unlike other radio navigation equipment (GPS, VOR, ADF), the DME unit in the aircraft is not only a radio receiver, it is also a transmitter. If you lose your alternator and are running on battery power, transmitters such as the DME and transponder should be turned off because they consume a lot of power.

It should also be noted that there is nothing that a DME can do that a GPS cannot do better.

Exercise 57 *Sometimes during an instrument approach it is necessary to fly part of a circle around a DME at a fixed distance, say 12 nm. If the arc is being flown accurately at 120 knots IAS, what ground speed will be displayed on the DME?*

7.9 Answers to Exercises

This section contains possible answers to the exercises in this chapter.

Exercise 48

If you were to observe the radio waves, you would find that 114,600,000 peaks passed you every second. Since each peak is travelling at 299,792,458 metres per second, the distance between peaks (traditionally designated as λ) must be:

$$\lambda = \frac{299792458}{114600000} \text{ metres} = 2.615990035 \text{ metres}$$

Exercise 49

Applying formula 7.1:

$$1.23 \times \sqrt{5500 + 935} = 1.23 \times 80.2 \approx 99 \text{ nm.}$$

The VORTAC should be receivable from approximately 99 nm away.

Exercise 50

Turn to the heading of 045° and tune and identify the VOR. As the VOR's CDI needle centres (with a FROM flag!) turn onto a track (not heading) of 085° as indicated by the GPS. Note the heading you are flying and continue to fly it. The VOR's CDI needle should remain centred.

Exercise 51

Assuming that the receiver has been correctly tuned and the transmitter has been identified, following the steps given above:

1. The FROM flag indicates that if the aircraft were to fly a track of 254° then it would be going away *from* the VOR. Note that there is no information on the VOR about whether the aircraft actually is flying towards or away from the VOR.
2. The needle being centred indicates that a track of 254° would take the aircraft *directly* away from the VOR.

Exercise 52

Assuming you have a hand-held GPS the steps would be as follows:

1. Tune and identify the VOR.
2. Use the OBS to set 100° at the top of the VOR display.
3. Check that the VOR's CDI/indexCDI needle deflects to the left, indicating that if you were to fly a track of 100° you would need to turn left to intercept the radial. Check that a FROM flag appears.
4. Since you are flying away from the VOR, you may choose to intercept at 45°. $100° - 45° = 55°$ so you should use your GPS to fly a track of 055°. To double-check the GPS, confirm that the heading indicator is showing a heading of approximately 055°.
5. As the VOR's CDI needle centres, turn onto a track as shown by the GPS of 100° and monitor that the VOR's CDI needle remains in the centre. If not then make the necessary heading changes (this should not be necessary if you are flying the correct track accurately).

Exercise 53

A simple aviation calculator will show that, if you're tracking 270° inbound to the VOR, your ground speed is 71.3 knots and your heading is 276°. Given that ground speed, it would actually take you 25 minutes 15 seconds to reach the VOR.

Because you have no way of flying a track once you leave the VOR radial, in accordance with the time and distance formula, you will turn right 90° to a

heading of 006°. Your ground speed is now just over 97 knots and your track is 023°. Flying that track, the distance to reach the 080° radial will be 6.24 nm. That will take 231 seconds.

You therefore perform the following calculation

$$\frac{\text{Time in secs between radials}}{\text{Difference in radials}} = \frac{231}{10} = 23.1$$

and deduce that it will take you 23 mins 6 secs to reach the VOR. At this point you are actually 3 nm further from the VOR than you were when you started the exercise, and it will actually take you 27 mins 9 secs to reach it at your new ground speed of 72.9 knots. The error in timing is 4 mins 3 secs: an error of 17%—hardly precision flying.

Exercise 54

The pilot has turned the backing card on the ADF to put the aircraft's heading (050°) at the top. This means that the display will perform the necessary arithmetic. The needle is pointing to 190° and so the aircraft should be turned to 190° to point directly at the NDB.

Exercise 55

With a moveable card ADF this is simple. After tuning and identifying the NDB, turn the moveable card so that your heading (020°) is at the top. The situation will be as illustrated on the left-hand side of figure 7.21. As you move northwards the ADF needle will swing towards the 090° position and when it reaches it you have reached the interception point and should turn to 090°. The ADF card has effectively carried out the simple addition for you: 020° + 070° = 090°. In this case the arithmetic was very simple and you could have performed it mentally. In a more difficult case, the moveable card is your friend.

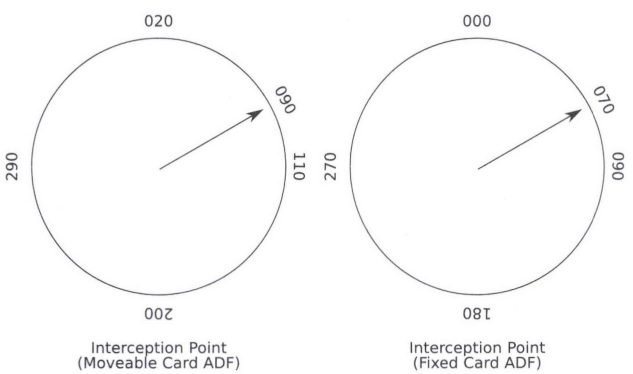

Figure 7.21: Solution of Exercise 55

With a fixed card ADF you must do the arithmetic yourself and conclude that you have reached the interception point when the needle is in the same position on the ADF but now pointing to 070°; see the right-hand side of figure 7.21.

Figure 7.21 also shows that rotating the card on the ADF does not affected the position of the needle—unlike a VOR.

Exercise 56 The VOR is out of service. You are hearing the identification of the associated DME.

Exercise 57 If the pilot is flying accurately, then the aircraft will be a constant distance of 12 nm from the DME station. The ground speed calculated by the DME receiver will therefore be 0 kts. This is actually a useful indication when flying such an approach—keep the displayed ground speed at 0 kts.

Chapter 8

Pilot Navigation

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This chapter deals with pilot navigation—navigating by comparing what is passing below the aircraft with a map (either paper or on a tablet). The topics covered here need to be understood to pass the Transport Canada written examination, but given the increased reliance on radio navigation (particularly GPS), some of these topics are not as relevant to actual flight as they once were.

Similarly most flight preparation is carried out using an application such as Foreflight, FltPlan or Garmin Pilot on a tablet. This chapter covers the preparation of paper maps and flight using pilot navigation, but it must be accepted that these are unlikely to be used in practice.

8.1 Pre-Flight Preparation

8.1.1 Map Preparation

Once the route is chosen, if you are using a paper chart other than a LO-chart,[1] draw the proposed route of flight in pencil on the chart. Unless you are preparing for a flight test, do not bother with 10° drift lines (see section 8.2.5). Depending on your aircraft type, mark distances along the proposed track. For a Cessna 150 cruising at 80 KTAS, these marks could be at 20 nm increments; for a Piper Arrow cruising at 130 KTAS, they could be at 30 nm increments.

8.1.2 Selection of Checkpoints

A checkpoint is a predetermined point along the route that can be used to assess the progress being made—is the headwind stronger than anticipated, is the aircraft still on the planned route, etc.?

When selecting checkpoints, it is tempting to use a feature that is obvious on the map, but difficult to spot on the ground. A VOR is very clear on a map but, unless you're using radio navigation, is difficult to spot on the ground, particularly if the ground is snow-covered. If possible, checkpoints should be chosen to be visible from the pilot's side of the aircraft.

A good checkpoint defines a point precisely. A road, power line, railway or river that you will cross almost at right-angles is generally not a good checkpoint as it may not be possible to determine at which point you have crossed it. For this reason, when navigation by ground reference was more common than it is today, pilots would often deliberately aim a few degrees off track so that, when they reached the river they were aiming for, they would know which way to turn to find their destination.

Distinctively-shaped lakes (in summer), bridges, airports and towns make good checkpoints.

[1] Even if you are using a LO-chart as the primary map, it can be useful to carry a VNC on board as well: if you are forced to descend because of icing or other weather, then the additional information on a VNC may be crucial.

8.1.3 Measuring Track & Distance

Unless you are using a LO-Chart or computer with a waypoint database, you will need to measure the bearing of the proposed track and the distance of each leg. Each of these hides a trap into which you may fall:

1. When measuring distance, ensure that you are using the scale appropriate for the map (VNC or VTA) and that you are reading a scale in nautical rather than statute miles. To avoid error, it is probably best to check by measuring a distance you know (e.g., the ring around a VOR, which normally has a radius of 10 nm on a VNC).
2. When measuring a bearing, remember that unless you are flying directly north or south along a line of longitude, the bearing of a great circle route changes at every instant. To get a reasonable approximation for short legs (up to a hundred nautical miles or so) while flying in the lower latitudes, use a point close to the centre of the leg and measure against a line of longitude, remembering that the resulting bearing is True rather than Magnetic. If there is a Victor Airway parallel with the desired track, and you use its bearing, remember that it will be Magnetic, not True. See section 10.2 for an explanation of the difference between Magnetic and True bearings.

The technique given in point 2 for estimating a bearing only works for flights where the convergence of lines of longitude towards the north pole can be neglected. This is true of short flights well away from the north pole. At higher latitudes this technique breaks down and *Grid Direction* has to be used. It is not necessary to understand this technique for the Transport Canada written examination but aerodromes in the north, have a *grivation* value. Lutselk'e, for example, has a grivation of 131° East. These values allow navigation without using latitude and longitude, using a grid instead. The grid is constructed by choosing a line of longitude (often the Greenwich Meridian) and assuming that the true north pole is infinitely distant along that line. Other lines can then be drawn parallel with, and perpendicular to, this line, creating a grid.

8.1.4 Setting Heading

A set-heading point is an initial waypoint, and selecting a set-heading point can be useful when you are in unfamiliar and largely featureless terrain and have no flight-planning software available. A set-heading point is chosen to be easily found and very clearly identifiable from the air. Sometimes the departure airport may be the only suitable set-heading point.

The purpose of selecting a set-heading point is to allow the final cruise altitude to be reached before setting off on the first leg of the flight. This was necessary before the days of flight planning software and GPS navigation because, in manual calculations, the climb and cruise had to be treated separately for fuel calculation and timing purposes. Most modern flight-planning software can perform the compound calculation, which is why set-heading points are effectively obsolete.

Where they are used, fly to the chosen set-heading point and, if necessary, circle it to reach the cruise altitude. Then, level the aircraft and reset the heading indicator from the compass. You should aim to cross the set-heading point on the heading you calculated for the first leg. As you cross the set-heading point, record the time and check the track visually: e.g., "I should be crossing the river almost at right angles and the lake should be dropping behind my left wing".

8.1.5 Triangle of Velocities

See appendix F.

8.1.6 Navigation Computers

See appendix C.

8.2 Flying the Planned Route

8.2.1 Map Reading

During a VFR flight when navigating by map reading (rather than radio navigation), it is often tempting to "micro-manage". Instead of picking some large feature on the route of flight (a city, distinctive lake, intersection of power lines, etc.) as far ahead as possible and then flying to it, many pilots try to check off every minor feature (road, village, etc.). This can lead to stress, cockpit overload and concern when some ground feature has changed since the map was printed. Remember that maps can also be wrong: several towers close to the main Ottawa to Montréal highway, for example, have been shown on the VNC chart on the wrong side of the road for many years. This type of error can disconcert you if you are micro-map-reading.

Anecdote 22 *During my PPL flight test, the examiner asked me to identify on the ground a field clearly shown on the map as containing several towers. I found what appeared to be the field, but it contained no towers. Working from other evidence (positions of roads, rivers), I pointed to it and declared that the towers must have been removed. Apparently that was the correct answer.*

The general technique when map reading is to identify a significant feature on the map lying on or close to your track and then identify it as it appears before you. Remember that not all features on the ground will be on the map but (errors aside) all features on the map should be on the ground; therefore, select features from the map rather than ones on the ground. Each feature should be identified, if possible, by three independent characteristics. Often, for example, a railway line will follow a river, and identifying a town because it lies on the railway line and the river is likely to be erroneous, as looking left and right you will probably see other towns on the same railway line and river. It is better to select features that not all towns in the area will have. For example, "the town lies to the north of the river, has a railway *intersection* and a sports stadium on its eastern edge".

This method can also provide a useful measurement of visibility—needed for an objective judgement of whether the visibility is deteriorating. Pick a ground feature as far ahead as you can see, identify it on your map and measure the distance. If you are not sure of your current position on the map then note the distance your GPS is displaying to your next waypoint. As you fly over the chosen feature, note the GPS distance again: this is an estimate of your flight visibility. Doing this regularly will enable you to determine objectively whether you are flying towards an area of deteriorating visibility. If you have no GPS available, then use a stop-watch instead. For example, if you have calculated your ground speed as 100 knots and it took you 12 minutes to fly to the distant feature, then you can conclude that your visibility was at least $100 \times \frac{12}{60} = 20$ nm.

8.2.2 Position Lines

A position line is a line that matches a path on your map to the corresponding path on the ground. The line joining two distinctively-shaped lakes would be an example of a position line and you could identify being on this position line by seeing the lakes passing your left and right wingtips.

Another example of a position line is a radial from a VOR; VOR navigation is primarily carried out using such position lines.

In general, if you can determine two position lines, preferably almost at right angles to each other, you can determine your position on the map very precisely: "I am on the position line joining those two lakes and also on the 140° radial from that VOR so I must be *here*".

8.2.3 Ground Speed Checks

If you have a GPS available, then your ground speed and current Estimated Time of Arrival (ETA) can be read from it continuously. Even if you have a GPS, it is worth marking these on the map or flight log periodically in case the GPS fails and you need to resume manual navigation.

If you do not have a GPS available, at each checkpoint you should calculate your average ground speed manually as in exercise 58.

Exercise 58 *You have flown 124 nm since leaving your set-heading point and 24 nm since your previous checkpoint. You passed your set-heading point at 12:00 and the time is now 13:16. You crossed your previous waypoint at 13:02. The total distance of your flight from the set-heading point is 212 nm. What is your ETA?*

Note that neither the predicted ETA calculated manually, nor that read from the GPS takes into account changes of track. They assume that the rest of the journey will be completed at the ground speed you are currently achieving. If your track turns into wind between your present position and your destination then the ETA provided by the calculation or GPS will be over-optimistic.

8.2.4 Track Made Good (TMG)

The Track Made Good is simply the track your aircraft has followed across the ground.

8.2.5 Regaining Track

These techniques represent perhaps the most impractical part of Transport Canada's syllabus. They rely on the assumptions that you are navigating without the help of any radio navigation aids (VORs, GPSs, etc.) and that the only reason you are off course is because of an error in the estimated winds. You are not off course because of slightly inaccurate flying or because ATC vectored you around some traffic.

This is worth emphasising: if you are off your planned course because of any reason other than the winds being not as anticipated, then the methods described here will not work to get you back on course.

However, the idea is simple. Draw lines at 10° either side of the track you intend to fly across the ground. This will enable you to estimate the angle by which you're off course. You can then apply a rule of thumb to find your way back on course.

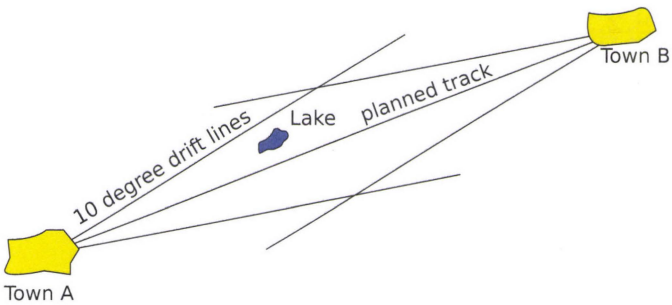

Figure 8.1: Using 10° Drift Lines

Consider figure 8.1 and imagine that you intended to fly from Town A to Town B along the straight line track indicated. Unfortunately, after 25 minutes of flying you find yourself over the middle of the lake, somewhat to the north of the planned track. If you are sure that you have been flying your calculated heading of, say, 060° very precisely and the only reason that you are off course is because the winds aloft were not as forecast, then you can use one or other of the following techniques to get back on course:

1. *Double Track Error Method.* Using the 10° drift lines, estimate your angle error. In figure 8.1 it appears to be about 5°. Double this angle to give 10° and turn right by this amount to a new heading of 070°. Fly this heading (accurately!) for a further 25 minutes and this should get you back on track. Now turn left by the amount that you were off course (5°) to a heading of 065° and continue your trip to Town B. This technique will only work in the first half of the journey, because, if applied in the second half, you will overshoot your destination.

2. *Opening and Closing Angle Method.* Using the 10° drift lines, estimate the angle error from both from Town A and Town B: say 5° from Town A and 3° from Town B in figure 8.1. Add these two numbers together to get 8° and turn right by this amount to a heading of 068°. This is claimed to bring you back on course at Town B. This technique has the advantage of "working" at any point in the flight.

As exercise 59 shows, the double angle method can be very accurate if it were possible to fly on the selected heading and if the wind remained constant during the flight.

Exercise 59 *You are flying an aircraft with an airspeed of 100 knots and wish to fly a track of due east (090). The upper winds are forecast to be calm at the altitude at which you will be flying and you have therefore made no adjustment for drift and are flying a heading of 090°. After 25 minutes of flying you find yourself 8° south of track because of an unexpected wind from the north. Applying the double angle method, you turn left 16° and fly for a further 25 minutes. How far will you then be from your intended easterly track?*

8.2.6 Visual Alteration for Correcting Track

This makes more sense than the other methods of regaining track, and it's what pilots do all of the time when diverting to an unplanned aerodrome. You notice that the lake which should be passing to your left is directly underneath. So you turn right to regain the correct track over the ground. If you can see another landmark ahead that should also be on your track, then fly to it.

8.2.7 Diversion to Alternate

There are many reasons why you might change your destination and fly to a different aerodrome. Perhaps the weather is deteriorating at your current location or at your destination, perhaps you have met unexpected headwinds and your fuel may be inadequate to reach your destination, or perhaps you have a sick passenger or aircraft and need to land as soon as possible.

Whatever the reason, make the decision to divert as early as possible (particularly if flying into deteriorating weather) and as decisively as possible—once you have made your decision there is always a tendency to think "well, perhaps I could make it to my original destination," particularly if there is some compelling reason to get there. Such decisions are better made on the ground.

Selecting the new destination may be as simple as pressing the *NEAREST AIRPORTS* button on your GPS, particularly if you have already programmed it to display only airports suitable for your aircraft (e.g., hard-surfaced runway at least 1,500 ft long). Even the simplest hand-held GPS will give you your expected time *en route*, the track to fly, airport details (e.g., elevation, runways and radio frequencies) and the height of terrain between you and the airport.

If you don't have a GPS available, then you will need to glean the same information from your map or from ATC. If you have a problem with the aircraft or are experiencing deteriorating weather, then make use of ATC as much as possible for navigation: "Toronto Centre, Papa Tango November has very high oil temperature, request immediate vectors to Peterborough airport." "Papa Tango November turn right heading

340, Peterborough is at your twelve o'clock and 12 miles. Report Peterborough in sight". ATC will help, and apart from a telephone call once on the ground to say that you have landed safely, there is likely to be no follow-up.

Anecdote 23 *This anecdote records the same incident as anecdote 43, but with a different moral.*

A situation similar to the example above occurred to me once while flying from Ottawa Rockcliffe to Kingston, Ontario. Somewhere south of Carp (CYRP) airport the oil temperature gauge went to full-scale. The oil pressure seemed to be holding, but I had to assume that the engine might stop at any time. I told ATC of the problem and asked for vectors to Smiths Falls which I assumed to be the closest airport. ATC gave me those vectors but told me that I was slightly closer to Carp and offered me vectors there. I accepted and ATC contacted Carp directly to tell them that an aircraft with a problem was approaching at high altitude from the south. Although the engine kept running to the ground, being able to offload navigation onto ATC was an invaluable help.

Ensure that you have sufficient fuel to reach the new destination and are sufficiently high to avoid obstacles and terrain, then immediately turn towards it, adjusting your course as you fly. If there is a ground feature (e.g., river, road, railway line) that will lead you to the new destination it might be wise to follow it, even though the route might be slightly longer.

When you are *en route* to the new destination ensure that ATC knows where you are going and, if possible, inform the nearest Flight Service Station of your change of destination and estimated time of arrival. Remember, however, that your first priority is not to inform people but to fly the aircraft and reach your new destination safely—you should aviate, navigate and then communicate, in that order.

8.2.8 Return to Departure Point

To return to your departure point, perhaps because of deteriorating weather, carry out the following procedure:

1. Reset your heading indicator from the compass and record (on your map or kneepad) your current heading. If you know your current track (perhaps from your GPS, perhaps from calculations), also record it. If you do not have a track value then estimate it from your heading.
2. Deduce the reciprocal track by adding or subtracting 180° from your current track. If you have a VOR or ADF that is not being used, then this calculation can be reliably performed by using the OBS to set your current track at the bottom and reading the reciprocal off the top. This also gives you a useful *aide-mémoire* for the track you should be flying.
3. Start a turn to the reciprocal track.
4. Calculate an appropriate heading to fly to maintain the return track given the difference in heading and track outbound. This is obviously trivial if you have a GPS on board, otherwise it must be done by estimation. Turn to that heading.

Exercise 60 *You are flying a heading of* 125° *and tracking* 130°. *What heading would you fly to return to your departure point?*

8.2.9 Low Level Navigation

Navigating at low level, say between 500 and 3,000 ft AGL, is much more difficult than navigating at higher altitudes because it is difficult to form the larger picture of the landscape. Also, fewer radio navigation devices will be in range. The difficulty in forming the big picture view of the landscape is particularly evident if you have been forced down to low altitude because of a descending cloud base which may be accompanied by reduced visibility.

The following guidelines might be useful when navigating visually at low level:

- Slow down to a safe cruise speed. Things appear to pass much more quickly at low level. Be aware however, that if the weather is deteriorating, slowing down may make the problem worse by keeping you in it for longer.
- Be aware of illusions caused by drift—see section 2.11.1 on page 44. These are much more prevalent at low level and can, in extreme situations, cause stalls during turns.
- Avoid fixating on the view ahead. Rather keep a scan from your 9 o'clock to your 3 o'clock position. At low level it is very easy to let the airport or town you are seeking pass off your wing while you are concentrating on the view ahead. If you have passengers, conscript them to help spot waypoints.
- Fly your headings and speed precisely and trust your calculations. DED reckoning can be uncannily accurate. Once you have found the approximate wind speed and direction you should be able to fly

for 20 minutes or so and pass over your next waypoint within 60 seconds of your calculated time.

8.2.10 Deduced Reckoning

DED (sometimes spelled "Dead") reckoning is the process of estimating your current position based upon a previously known position, your ground speed, elapsed time and course. Effectively you are saying: "20 minutes ago I was *there* and since then I have flown with a ground speed of 103 knots on a track of 125°, so I must now be *here*".

8.2.11 In-Flight Log

The purpose of an in-flight log is to allow you to predict the time you will pass your next fix and reach your destination. This allows you to determine, for example, whether unexpected headwinds will make it necessary to stop at an intermediate airport for extra fuel. It is also useful when you are uncertain of your position (see section 8.2.13).

FIX	ST	LAT/LON	In/Out Mag Crs	Leg	Rem	Fuel Burn Leg	Fuel Burn Tot.	Leg	Rem	ETE	ATA	WX
CYRO OTTAWA	ON	N4527.6W07538.6	---/073	0	294	2.2	2	0:00	2:52	0:00		
TAKOL	CN	N4539.0W07511.9	072/079	22	272	2.3	5	0:15	2:37	0:15		N/A
IPSAK	CN	N4545.4W07451.5	079/079	16	256	.9	5	0:08	2:29	0:23		N/A
BOKLU	CN	N4550.4W07435.7	079/080	12	244	.7	6	0:07	2:22	0:30		N/A
EMPEK	CN	N4555.0W07420.7	080/080	11	233	.6	7	0:06	2:16	0:36		N/A
ESTEL	CN	N4557.9W07411.0	080/080	7	226	.4	7	0:04	2:12	0:40		N/A
TAMKO	CN	N4602.9W07354.6	080/080	12	214	.7	8	0:07	2:05	0:47		N/A
AGLUK	CN	N4612.6W07322.2	081/081	25	189	1.5	9	0:14	1:51	1:01		N/A
NOVID	CN	N4615.1W07313.4	081/082	7	182	.4	10	0:04	1:47	1:05		N/A
SOKYE	CN	N4621.5W07251.1	082/082	17	165	1.0	11	0:09	1:38	1:14		N/A
KETRU	CN	N4627.2W07231.3	082/082	15	150	.9	12	0:08	1:30	1:22		N/A
PESAC	CN	N4632.9W07211.2	082/082	15	135	.9	13	0:09	1:21	1:31		N/A
YQB 112.8 QUEBEC	CN	N4642.3W07137.6	084/086	25	110	1.5	14	0:14	1:07	1:45		N/A
FLEUR 112.8/86/51	CN	N4659.3W07027.8	086/053	51	59	3.0	17	0:28	0:39	2:13		N/A
ANATI	CN	N4745.4W06935.3	053/032	58	1	4.3	21	0:38	0:01	2:51		N/A
CYRI 113.9 RIVIERE DU L	QC	N4745.9W06935.1	035/---	1	0	.1	21	0:01	0:00	2:52		

Elev:427 AWOS: 122.02 CTAF: 122.77 Fuel hourly method: 23

ALTN: CYYY MONT-JOLI MONT JOLI QC | Alt: FL070 Brg:065° 75nm Time:0:44 Fuel:6

Fuel (gal.) | Taxi: 2.2 | Trip: 19.3 | Altn: 5.7 | 45 min: 5.0 | Min Fuel Required: 32

AVIATION MH 122.77 418-867-5001 | ARCAL LGTS TYPE J 122.77 | FSS Arrival Airport 866-541-4105 (ACC:514-633-3211)

07/14	Sunrise	Sunset
CYRO	5:27	20:49
CYRI	4:54	20:34

in:	on:	Start:	
out:	off:	Rem:	
Block Time:	Flight Time:	Fuel Used:	

Figure 8.2: A Log for a Flight from CYRO to CYRI

The actual format of the log is not important. What is important is the information it contains. Most software flight planning applications prepare a log of the type illustrated in figure 8.2, where the pilot adds the actual times in the ATA column during the flight. One advantage of using a software application to prepare the log is that it is aware of intermediate waypoints, so these do not need to be entered manually. The log in figure 8.2, for example, was generated by entering the route

```
TAKOL T731 AGLUK T781 YQB T660 ANATI
```

and that route was suggested by the application as one which other aircraft had recently flown. If a suitable software application is not available, the log information can be marked on the map, on a prescribed form or simply written informally on a pad.

The flight log shown in figure 8.3 was designed specifically for IFR flight but can also be used for VFR flight, particularly flight along airways. While on the ground before the flight, enter the waypoints in the left-hand column and the magnetic track, frequencies of navigation aids, distance between waypoints and total miles left. Of course, getting an application to do this (as in figure 8.2) is much easier.

Once in the air, the actual time travelled between the first two waypoints is measured and the ground speed calculated. This result is then used to predict the time at the next waypoint and the approximate time the final destination will be reached. This process is then repeated at each waypoint.

Do not become too reliant on flight logs of this type because:

- particularly when flying IFR, or VFR in congested airspace, it is likely that you will be re-routed: "Papa Tango November, fly heading 120 for traffic" and, perhaps 10 minutes later, "Papa Tango November, traffic is no longer a factor, resume own navigation". In this case the log can become a liability rather than an asset. Even if you are not re-routed by ATC, you may wish to re-route to avoid low-hanging cloud or a thunderstorm, and a fixation with the route originally planned may lead you into trouble.

- unless your track to destination is a straight line, your calculated time to destination will be inaccurate because, as you turn a corner, the relative wind direction will change.

- even the cheapest hand-held GPS will give you your ground speed, time to next waypoint and time to destination without you having to do any calculations. If you have a GPS, use it, but:

  - ensure what the GPS is telling you makes sense. For example, there is a VOR in Ontario with the identifier YCF. There is also a VOR in South America with the same identifier. Unless you notice the distance to the fix, you could easily fly an unintended track towards the wrong one. Always double-check the numbers!

  - write down what the GPS is telling you at each waypoint. If the GPS fails, then you will have this as backup.

Enroute Flight Log				Estimated		Actual				
Fix	Mag Crs	Route	Freq	ETA Next Fix	Est Mins Fix	Time Over Fix	Elapsed Time	Miles to Fix	Gnd Spd	Total Miles Left
	⇐ Departure Point							Total Miles ⇒		

Cleared To:	Via:	Squawk:	Altitude/Frequency

Engine On	Take Off	Landing	Engine Off	Fuel Calc	
				To Dest:	
				To Alt:	
				Apprch:	
				Reserve:	
				Required:	
				Onbd:	
				Extra:	

Figure 8.3: Sample In-Flight Log

Anecdote 24 *My wife and I were leaving North Bay, Ontario for the short flight to Killarney. My wife looked up the identifier for Killarney in the CFS and punched it into our GPS. I started to fly the track it gave. After a few miles it was clear that Lake Nipissing, over which we should have been flying, was disappearing to the south of us. After some moments of confusion we realised that we were heading towards Killarney, Manitoba, not to Killarney, Ontario. Luckily we were in VFR conditions, but it is interesting to speculate how long it would have taken us to notice the error had we been flying IFR and taken off into a 600 ft cloud base. As it says above:* ensure that what the GPS is telling you makes sense.

8.2.12 In-Flight Calculations

Where possible, avoid mental calculations while flying because you are liable to make mistakes. Instead, use the equipment in the aircraft as much as possible to avoid having to perform mental calculations. For example, to calculate the reciprocal of a particular track or heading, instead of adding or subtracting 180 mentally, turn a VOR or ADF card until the track or heading is at the top and then read the reciprocal at the bottom.

There are some simple inflight calculations you may wish to perform, including the following.

- Start of descent. Many hand-held GPSs have a feature that provides a "glideslope" to bring you to circuit height (e.g., 1,000 ft AGL) 2 nm (or whatever you specify) before reaching your destination airport. If you do not have this feature, then you will have to calculate at what point to begin your descent. A descent rate of 500 ft per minute is comfortable in most light aircraft and the calculation would seem to be simple: assume 2 minutes for each 1,000 ft to be dropped. In fact this is not accurate because you can expect to fly the descent faster than cruise. For this reason use a descent rate 100 ft per minute more than the actual descent rate in the calculation—say 600 ft per minute.

- Timing can, in principle, be used to turn to a particular heading if your heading indicator is defective. Since an aircraft takes 120 seconds to turn through 360° in a rate 1 turn, it is easy to calculate the time required to turn through any particular angle: 3° per second. To turn through 20°, for example, roll into a rate one turn and roll out after $\frac{20}{3} = 6.66$ seconds.

  In fact this calculation is inaccurate because it doesn't take into account the time taken to roll into and out of the turn. In any case, it should rarely be needed in a light aircraft. If you are in IMC without a functional heading indicator then you have an emergency and you should declare an emergency and request "non-gyro vectors" (see section 10.6.5 on page 225). If you are in VMC, then precision in the turn is not required: turn roughly in the direction required, wait for your compass to settle and then adjust your heading.

There are additionally some "rules of thumb" that can sometimes be useful when there is no time for more accurate calculations. The most commonly used one is that 1° off track is approximately 1 nm off track at 60 nm from the destination.

8.2.13 Procedures When Lost

The feeling of being lost in an aircraft is extremely disconcerting, particularly in deteriorating weather.

General Advice

The standard advice to a pilot who is lost consists of the "three Cs":

1. **Climb,** if possible, to get a better view of the terrain and ground features and to improve radio reception from navigation aids and ATC.

2. **Confess:** tell ATC you're lost and ask for help.

3. **Comply:** do what ATC suggests.

While these are all useful, sometimes the very reason for being lost may be that you are being forced down by a reducing cloud ceiling into an area of poor visibility and, because you are flying low, you are unable to contact ATC for help.

There is a tendency to react to the immediate pressure of being lost by feeling that you must *do something, anything, now!* There is a temptation to turn off course immediately to fly towards what appears to be better weather or an identifiable ground feature. This can be disastrous. Here is a more systematic way of tackling being lost:

1. Slow the aircraft down to a safe cruising speed and continue flying on your present heading while you:

   - record the time and your current heading on your map or kneepad. Do not try to remember these because your memory may betray you as the pressure builds.

- roughly estimate and record the time you will run out of fuel (e.g., "I started with 3 hours of fuel and have been flying for 1 hour 20 minutes so I expect to run out of fuel in 1 hour 40 minutes at 12:45 local time"). Don't bother with sophisticated calculations but, if you are flying an aircraft with a mixture control, look at it now: did you lean properly? If not, then lean now and recalculate when you will run out of fuel by adding, say, 50% to the time you have been flying.
- draw a circle around your last known position on the map and, if possible, mark the time that you were over it.
- draw a circle around the highest *Maximum Elevation Figure* for the areas over which you may be flying.
- if you have been keeping your Air Position (see *Air and Ground Position* on page 160), then draw a circle around this on your map as well.

2. With this preparation complete, assess your resources:

   - If you have a working GPS then your problem is immediately solved.
   - If you are in contact with ATC, ask them for your position. If you do not have a discrete transponder code, you will be given one, your position will be determined and ATC will give you vectors to your destination.
   - If you are not in contact with ATC, try to establish contact, climbing if necessary to make contact by radio or cellular telephone.[2] If you do not know a suitable radio frequency then use 126.7 MHz to contact a flight service station or 121.5 MHz to contact ATC, a flight service station or an over-flying aircraft. If you are very low, then contacting an over-flying commercial aircraft might be the best approach. If none of these are possible, use a cellular telephone to contact a local flight information centre—the telephone numbers of these are listed in section A of the CFS. It would be useful to have written this number on your knee-pad during your flight preparation.
   - If you are too low to contact ATC and cannot climb because of the cloud base, use your map to determine the frequency of the closest VOR or NDB and tune and identify this. If there are two such devices within range, you can identify your position exactly (see section 8.2.2). If there is only one device, draw the radial on the map and mark the closest point this comes to your estimated position.
   - Look out for a town with a water tower. This may seem silly, but many Canadian towns have labelled water towers and knowing the name of the town over which you are passing will fix your position on the map.

   Your passengers are another potential resource. Assess whether they are likely to be more of a help or hindrance if the situation is explained to them. If you believe that they would be helpful, inform them of the situation and instruct them to look for runways. Often they will be able to spot these when you, as pilot, are concentrating on other matters.

3. Having assessed your resources and looked at the map, decide on a plan of action. This will probably involve one or more of the following:

   - Fly directly towards (or away from) a navigation aid.
   - Find a ground feature on the map that cannot be missed and change heading to fly towards it (e.g., "the St Lawrence river runs west-to-east south of my current position. I will turn to a heading of due south until I reach the river in approximately 15 minutes and then turn East.")
   - Turn to a reciprocal track (see section 8.2.8) and attempt to fly back towards the last known point.

Ultimately, if the weather is deteriorating, the safest decision may be to make a precautionary landing in a suitable field. The decision to make such a landing should be made before the weather is so low that the choice of landing ground cannot be made safely and certainly before your aircraft is forced below the *Maximum Elevation Figure* or runs out of fuel.

DF Steer

A primitive system known as a Direction Finding (DF) Steer used to be available at some airports: look for the symbol *VDF* close to an airport on an old VNC. If you asked for a DF Steer, the operator (typically a flight service station specialist) would ask you to hold down your push-to-talk button for a few seconds while a directional antenna was used to locate your bearing from the station. You would then be asked to turn to a given heading and fly for a few minutes before depressing the push-to-talk button again. Given your airspeed, this

[2] Trying to use a cellular telephone in the cockpit of a noisy general-aviation aircraft will, of course, be difficult.

allowed the operator to determine your approximate range. The operator would then provide you with the track needed for you to fly directly to the station.

DF Steers are no longer available and, if you can contact a flight service station or ATC, then they will probably have secondary radar. They can give you a transponder code and know immediately where you are.

Declaring an Emergency

If you are lost, the situation might easily become an emergency. When it does, you may need to take an action which is in conflict with air law. You may, for example, make the decision that it would be safer to ascend into cloud in controlled airspace without a clearance than remain under a descending cloud ceiling. Remember that your first responsibility is the safety of yourself and your passengers.

Anecdote 25 *I was once flying from Ottawa Rockcliffe to Peterborough, Ontario to have some navigation equipment fitted. I had no working navigation equipment in the aircraft, but this did not worry me because I had flown to Peterborough many times and I knew that I only had to follow the electrical power lines. Visibility was poor (about 3 miles) and the cloud was low (1,500 ft AGL) and, being stupidly over-confident, I was not concentrating. Suddenly, glancing at the map, I realised that the power lines had divided behind me and I was unsure which power lines I was actually following. The feeling of disorientation was acute. I felt in my flight bag for my hand-held GPS, but I had not packed it—another mistake. After some minutes of panic, I remembered that my hand-held radio had a VOR receiver built in. I used this to get a fix off two VORs and found, to my intense relief, that I was following the correct power lines.*

8.2.14 Air & Ground Position

Your air position is the position where your aircraft would have been, had there been no wind, given the headings and times of each leg you have flown. The difference between your air position and ground (actual) position is therefore entirely due to wind. It is not suggested that you plot your air position but you should record the heading and duration of each leg so that, should you become lost, you can draw these on your map and determine your air position. This can then be used as a first approximation of your ground position.

8.2.15 Variation/Deviation

The simplest device we have for determining direction is the magnetic compass. This relies on the earth's magnetic field which is generated in the earth's fluid outer core by electrical currents flowing in the slowly moving molten iron.

Unfortunately, as explained in section 10.2 on page 209, a compass doesn't point at the actual North Pole but instead to the Magnetic North Pole.

The difference between the True and Magnetic North Poles means that to determine true tracks and headings (i.e., those relative to the True North Pole), corrections have to be made in the magnetic tracks and headings (i.e., those relative to the Magnetic North Pole).

8.2.16 True & Magnetic Track

Unless there is no wind, an aircraft points in a direction different from the direction it is travelling across the ground. Imagine a canoe being paddled across a river in which a strong current is flowing. If the canoe is pointed straight across the river, it will travel downstream as it crosses. If the intention is to travel directly across the river, the canoe must be pointed upstream and part of the paddling effort must be undertaken to fight the current and part to cross the river. This is similar to an aircraft flying in the presence of wind.

The direction in which the aircraft is pointing is called its *heading*. The direction in which it is travelling across the ground is called its *track*. The speed at which it moves through the air is called its *airspeed* and the speed at which it moves across the ground is called its *ground speed*. A GPS, for example, displays track and ground speed. The aircraft's heading indicator displays heading while the airspeed indicator, eponymously, shows airspeed.

The angle between a track and a line joining the current position to the True North Pole (e.g., from a line of longitude on a map) is called a True Track. The angle between a track and a line joining the current position to the Magnetic North Pole (e.g., from a VOR radial in the southern domestic airspace) is called a Magnetic Track.

8.2.17 True & Magnetic Headings

Headings and tracks are measured from True or Magnetic north in a clockwise direction. North is designated 000° or 360°, east 090°, south 180° and west 270°.

As described above, the magnetic compass in an aircraft points to the magnetic north pole, not the true north pole. This means that corrections have to be made when converting between the two.

Exam Hint 18 *In examinations as well as the real world, it is common for some directions to be given as magnetic, some as true, some as headings and some as tracks. Before manipulating directions, ensure that they are in a common unit of measurement.*

Exercise 61 *The magnetic variation at Rockcliffe Airport is 14° West. An aircraft parks on the ramp directly facing Polaris, the north star. What does its compass read?*

Exercise 62 *The METAR for Gatineau, Québec airport (where the magnetic variation is 14° west) reports the wind as being from 320° at 20 knots. How many degrees off runway 27 is the wind?*

8.2.18 Airspeeds

One of the surprises that awaits student pilots on their first cross-country is that the aircraft doesn't perform as well in the air as it says in the handbook. Perhaps they have flight-planned for an airspeed of 105 knots as stated in the POH, but a glance at the airspeed indicator shows that the aircraft is perhaps only achieving 95 knots. A dual cross-country is often the first sustained straight-and-level flight the student has undertaken and this lack of performance comes as a surprise.

Actually, of course, this is just a confusion between *true* and *indicated* airspeed.

True Airspeed (TAS) is the genuine speed at which the aircraft is moving through the air.

Indicated Airspeed (IAS) is the speed indicated on the face of the airspeed indicator.

Calibrated Airspeed (CAS) is the indicated airspeed corrected, according to the table in the Pilot Operating Handbook (POH) to account for the intrinsic errors in the aircraft's system.

The conventional pitot-static airspeed indicator fitted to most aircraft gives a poor approximation of the actual speed at which the aircraft is moving through the air. As a rule of thumb, the TAS can be approximated by reading the airspeed indicator (correcting the IAS to CAS if the difference in the POH is significant) and adding 2% of the indicated airspeed per 1,000 ft of altitude. This is not strictly correct because the correct calculation also involves the outside air temperature, but it may be sufficiently accurate in flight.

Exercise 63 *You are flying a Cessna 172 at a pressure altitude of 8,000 ft and your airspeed indicator reads 95 knots. What is your true airspeed?*

True airspeed can be found by entering the CAS, outside air temperature and pressure altitude into an aviation electronic calculator. Alternatively, some airspeed indicators (see figure 10.6 on page 204) have a circular slide-rule built in. By setting the outside air temperature across from the pressure altitude, the airspeed markings are adjusted to be more accurate.

Exercise 64 *By using an aviation calculator, calculate the true airspeed of a Cessna 172 flying at a pressure altitude of 8,500 ft with an outside air temperature of 10° C when the CAS (read from the IAS and corrected from the Cessna table) is 90 knots.*

8.2.19 Ground Speed

The ground speed of an aircraft is, eponymously, the speed at which it is travelling over the ground. A GPS displays ground speed, as does Distance Measuring Equipment (DME) when the aircraft is flying directly towards or away from a DME station (see page 147).

8.3 Answers to Exercises

This section contains possible answers to the examples in this chapter.

Exercise 58

In the air it may be easier to use a circular slide rule (e.g., the circular part of an E6B with the slide removed) than a digital calculator, although a simple 4-function calculator glued to a knee-pad can also be effective. The FltPlan Go application (section C.2 on page 347) also incorporates a 4-function calculator with large buttons. Section C.4 describes how the slide rule may be used, but this is summarised here.

Using a calculator. The calculation assumes that you will keep your current ground speed for the remainder of the journey. Your current ground speed can be calculated from the fact

that you travelled 24 nm in 14 minutes. Your ground speed has therefore been:

$$\frac{24 \times 60}{14} = 102.9 \text{ knots}$$

You have a further $212 - 124 = 88$ nm to travel and, if you keep a ground speed of 102.9 knots, this will take

$$\begin{aligned} \frac{88}{102.9} \text{ hours} &= 0.855 \text{ hours} \\ &= 0.855 \times 60 \text{ minutes} \\ &= 51 \text{ minutes} \end{aligned}$$

You can therefore expect to arrive 51 minutes from now, at 14:07.

Using a slide rule. You have travelled 24 nm in 14 minutes. Align 24 on the outer ring with 14 on the inner ring. You have $212 - 124 = 88$ nm left to fly so look at the number on the inner ring under 88 on the outer ring—the answer is 51. You can therefore expect to arrive in 51 minutes from now, at 14:07.

Exercise 59

This exercise is much harder than would be found on the Transport Canada written examination, but it is a good exercise to ensure that you have understood the triangle of velocities (see page 353).

Firstly draw a triangle of velocities and find that, to be 8° off track, the wind from the north must be at 14.1 knots and the aircraft's ground speed would have been 100.98 knots. After 25 minutes of such flying, you will be 5.86 nm south of the required easterly track.

You now turn onto a heading of 074° ($090° - 2 \times 8°$) and fly for another 25 minutes with a wind from the north assumed to still be 14.1 knots. Drawing another triangle of velocities will show that the actual track flown across the ground will be 082° and the ground speed will be 97.1 knots. In 25 minutes the aircraft will cover 40.46 nm and will be 0.229 nm (1,209 ft) from the desired easterly track.

Exercise 60

The reciprocal heading of 130° is $130° + 180° = 310°$. You have been crabbing 5° to the east on the way out so, as a first approximation to be corrected later, you should choose to crab 5° to the east on the way back: fly a heading of $310° + 5° = 315°$.

Exercise 61

When the aircraft is facing Polaris it is facing true north. Figure 8.4 (not to scale!) shows the situation. The aircraft is pointing 14° further east than magnetic north and so the compass will be reading 014.

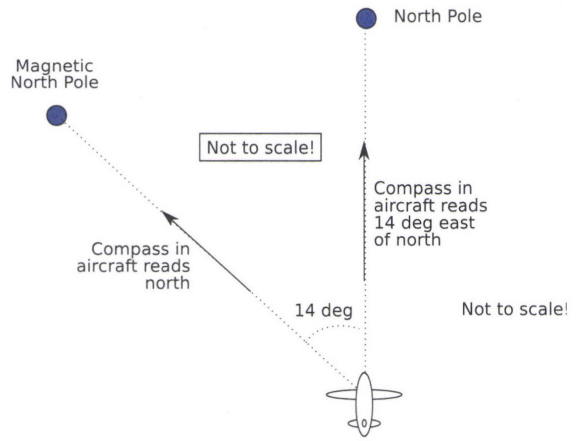

Figure 8.4: Situation for example, 61

Exercise 62

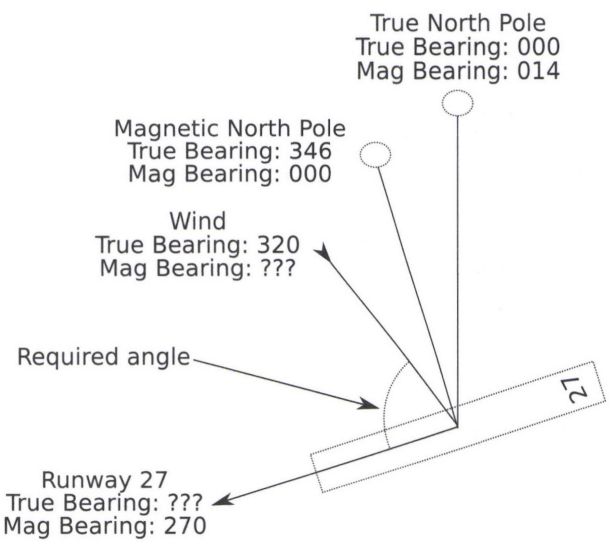

Figure 8.5: Situation for Example 62

METARs give the wind direction in degrees true. Runways in the southern domestic airspace are numbered in degrees magnetic. Figure 8.5 illustrates what you know and don't know—you need to find the angle between the wind direction (given in degrees clockwise from true north) and the runway (given in degrees clockwise from magnetic north). So you must either convert the wind direction to a magnetic bearing or the runway heading to a true bearing.

Converting the runway to true. The computation to convert the runway to a true bearing is as follows. The runway is facing a direction 270° from magnetic north. The magnetic north pole is 14° west of true north so, as can be seen from the picture, the runway is 270° − 14° = 256° from true north (it's runway 26T). The angle between the runway (256° T) and the wind (320° T) is 64°.

Converting the wind to magnetic. This computation proceeds as follows. The wind is coming from a direction 320° from true north. Looking at figure 8.5, it is clear that we need to add 14° to this to get a magnetic bearing. So the wind is coming from 320° + 14° = 334° magnetic. The angle between the runway (270° M) and the wind (334° M) is 64°.

The good news is that however the calculation is performed, the answer is the same: 64°.

Exercise 63

You calculate 2% of 95 knots to be 1.9 knots. Your true airspeed is then approximately

$$95 + (1.9 \times 8) \approx 110 \text{ knots}$$

Actually, on a standard pressure and temperature day, your true airspeed is 107 knots, so this calculation is reasonably accurate.

Exercise 64

Entering the information into an aviation calculator immediately returns a true airspeed of 104.2 knots. Notice that this represents a 14% error in the indicated (strictly "calibrated") airspeed.

Chapter 9

Theory of Flight

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The theory of flight addresses the question, *"how does something as heavy as an aircraft take off and stay in the air?"*

Answering that question involves some simple mathematics, and if you thumb through this chapter you will find mathematical formulæ scattered about. You do not need to memorise these for the Transport Canada examination, but do make notes of their important points. For example, it is useful to know that the parasitic drag on an aircraft increases with the square of its speed (double its speed and the parasitic drag increases four-fold). However, it is not important to learn the precise formula.

Many of the results in the theory of flight are remarkably old—for example, the idea of using dihedral to improve roll stability dates from 1808 when it was described by Sir George Cayley—aerodynamics is not a young science.

9.1 Fallacies

The theory of flight has been subject to basic misunderstandings since aircraft were first flown. Aerodynamics is changing as a result of more sophisticated experiments and new mathematical tools. If written 50 years ago, some sections of this chapter (e.g., section 9.3.7) would have been very different.

You have probably seen a picture of an aircraft in a banked attitude with a force marked "centrifugal" acting outwards on it.

You have also probably also seen a diagram like that shown in figure 9.31 on page 181 explaining that lift from a wing is generated by the air travelling over the top of the wing having further to travel than the air travelling beneath it, causing a lower pressure above the wing.[1] This fallacy is addressed on page 180.

You may understand that slats (section 9.3.7) work by introducing high energy air from the bottom of the wing to the top surface to re-energise the boundary layer.

You have probably heard about the P-factor of a propeller—the asymmetric thrust caused by different angles of attack on the downward- and upward-going blades—causing an aircraft to yaw during its takeoff roll.

These, and many other common stories about how aircraft fly, are either completely incorrect or, at best, over-simplifications of the truth.

This chapter attempts to strike a middle ground. In particular, it tries to give a mathematical explanation of why aircraft fly, without resorting to more than basic algebra.

9.2 Basic Concepts

This section gathers together a few of the concepts used repeatedly in this chapter.

9.2.1 Terminology

Some fairly uncommon words are used in this chapter. Some of them are described here.

Unit: Many measurements are based on a particular set of units. One person might say that he was 1.6 metres tall, while another might say he was 5 feet 3 inches tall. The numbers are different, but the heights are the same. A height has units, and it is inappropriate to say that a person is "1.8 tall" without specifying a unit.

Dimensionless: A measurement is "dimensionless" if it has no units. If someone says "today I am three times as old as my daughter", there are no units on the "three": it is dimensionless. Whether age is measured in years, months, days or seconds, the ratio is still three.

Coefficient: A coefficient is simply a number that specifies some factor of a system. A wing's *coefficient* of lift defines how much lift that wing can produce; a *coefficient* of restitution defines how high a particular ball will bounce if dropped.

Aerofoil: A shape designed to move through the air and cause the air to be deflected in a particular way. An aircraft's propeller, elevator and wing are aerofoils.

Equilibrium: An aircraft (or indeed any object) is said to be in equilibrium if there is no net force acting on it—all of the forces cancel each other out. A book lying on a desk in front of you is in equilibrium because there are only two forces acting on it, its weight acting downward and the force of the table acting upward, and these balance exactly. If the weight of an aircraft is equal to its lift and its drag is equal to the thrust then the aircraft is in equilibrium.

Directly and Inversely Proportional: Two related quantities are said to be *directly* proportional if they both get bigger or smaller together. For example, if you are driving a car on a highway with cruise control engaged, then the faster the car is driving, the more kilometers are covered each hour. The speed and distance covered are directly proportional.

Two related quantities are said to be *inversely* proportional if one gets bigger when the other gets smaller. For example, if you are driving a car from A to B, then the time taken to reach B is inversely proportional to your speed: increase your speed and the time taken will decrease.

9.2.2 Units

It may be worth reviewing the descriptions of mass and force provided in chapter 3 when considering this section.

The formulæ given for the examples in this chapter will work with either scientific units (kilograms, metres, seconds) or Imperial units (slugs, feet, seconds) provided that you are consistent in their use (e.g., you don't mix kilograms with feet). Scientific units are used in this chapter, but conversions of the answers into Imperial units are included for those who can visualise 2,300 lbs-force more easily than 10,231 newtons. Figure

[1] It is relatively easy to calculate that, if lift *were* created by the difference in pressure caused by different distances on the top and bottom of the wing then the stall speed of a Cessna 152 would be about 320 knots.

9.1 provides conversions for some of the values commonly used in the examples.

9.2.3 Letters

Various letters are used in the following sections. Rather than describe them each time they are used, they are gathered together in figure 9.2. Notes:

1. The density of the air (ρ: pronounced "rho" as in "a row of houses") is measured in kg per cubic metre and varies according to the atmospheric conditions. The standard sea level density is 1.2256 kg per cubic metre and at 40,000 ft (12,192 metres) it has reduced to 0.30267 kg per cubic metre. Figure 12.13 on page 272 gives values of ρ at other altitudes.

2. The area of a wing (A) is not the actual area of metal or fibreglass of which it is made. Instead, imagine the sun directly overhead the aircraft, casting a shadow of the wing on the ground. A is then the area of the shadow. Thus any curvature of the wing is excluded from the calculation.

3. The speed of the wing (v), relative to air sufficiently far away from the aircraft as to be unaffected by it, is measured in metres per second.

4. The four primary forces that act on an aircraft, lift (L), thrust (T), weight (W) and drag (D), are measured in newtons.

9.2.4 Newton's Laws of Motion

In 1687, Sir Isaac Newton propounded three laws of motion in his book *Philosophiae Naturalis Principia Mathematica*. Loosely-speaking they can be summarised as follows:

First Law. Unless you apply a force to a body it will remain stationary or, if already moving, will continue moving in a straight line at constant speed.

This may be obvious to us today, but before Newton it was thought that bodies came to rest if a force didn't keep pushing on them. So, when an arrow flew through the air, it was believed that there must be a force pushing on it all the time to keep it moving. Today we know that, unless there is a force acting on it (e.g., air resistance, gravity), it will keep moving in a straight line forever. On the moon, where there is no air resistance and gravity is weaker, the arrow will travel a lot further than it does on earth.

When an aircraft has no net force acting on it (i.e., it's in equilibrium) then, by Newton's first law it must be moving in a straight (not necessarily level!) line at a constant speed. It is particularly important to understand that an aircraft in a banked turn is *not* in equilibrium since there is a net force acting towards the centre of the circle causing it to turn.

Second Law. The larger the force you apply to a body, the faster will be the change in speed or direction of that body.

On the earth where gravity is stronger than on the moon, an arrow's flight will be bent towards the ground more than it would on the moon, so an arrow will fly further if fired on the moon.

Third Law. To every action there is an equal and opposite reaction, and the reaction acts on a different body.

If you fire a gun, then the bullet flies in one direction and the gun moves in the opposite direction (recoil). If the bullet has a mass of 1% of the mass of the gun, then it will accelerate 100 times as fast so that the momentum (mass × speed) of each is the same. Notice that the equal and opposite forces act on different things: one acts on the bullet, the other acts on the gun.

Each of these laws can be applied to the motion of an aircraft through the air. In particular the third law describes how an aircraft gets lift (see section 9.5.1) and the first and second laws describe how an aircraft turns by banking (see section 9.5.10).

9.2.5 Bernoulli's Theorem

Bernoulli's Theorem is another version of the principle of conservation of energy (see section 3.10). In its simplest form it says that, subject to a number of detailed conditions, if a gas or liquid speeds up, then its pressure falls. A gas under pressure has the potential to do work (e.g., the air under pressure in a child's balloon can blow something over if released) so, by virtue of its pressure, it contains energy—potential energy. As the fluid flows more quickly, its kinetic energy increases and, since energy cannot be created, its potential energy must fall: see figure 9.3.
Written algebraically:

$$\frac{v^2}{2} + \frac{p}{\rho} = \text{constant}$$

where v is the speed of the fluid, p is its pressure and ρ is its density. This equation says that if the speed of a fluid increases and its density remains the same, then its pressure must reduce in order to keep $\frac{v^2}{2} + \frac{p}{\rho}$ unchanged.

Strictly speaking, there are many conditions that have to apply for Bernoulli's Theorem to be valid, in

Value in Imperial Units	Value in Scientific Units	Notes
100 knots	51.5 metres per second	Cruise speed of a C172M
516 knots	265.5 metres per second	Cruise speed of a Boeing 747-200
500 ft per minute	2.542 metres per second	Typical descent rate for a C172M
2,300 lbs-force	10,231 newtons	Maximum weight of a C172M
637,000 lbs-force	2,833,500 newtons	Sample weight for a Boeing 747-200
174 square ft	16.2 square metres	Wing area of a C172M
5,500 square ft	511 square metres	Wing area of a Boeing 747-200
160 horsepower	119 kilowatts	C172M engine power

Figure 9.1: Some Conversions used in Examples

Letter	Pronounced	Meaning	Units	See ...
ρ	rho	Density of the air	kg per cubic metre	note 1
δ	delta	Max distance between chord and camber lines	metres	section 9.3.1
A		Area of the wing	square metres	note 2
v		Speed of the wing	metres per second	note 3
C_L		Coefficient of lift	dimensionless	section 9.5.1
C_{Dp}		Coefficient of parasitic drag	dimensionless	section 9.5.4
C_{Di}		Coefficient of induced drag	dimensionless	section 9.5.4
C_p		Coefficient of pressure	dimensionless	section 9.4.1
L		Amount of lift	newtons	note 4
D		Amount of drag	newtons	note 4
D_p		Amount of parasitic drag	newtons	note 4
D_i		Amount of induced drag	newtons	note 4
W		Weight of the aircraft	newtons	note 4
T		Thrust produced by the engines	newtons	note 4
r		Aspect ratio of a wing	dimensionless	page 170
η	eeter	Efficiency of a propeller	dimensionless	section 9.6.3
J		Advance ratio of a propeller	dimensionless	section 9.6.3
n		Load factor	dimensionless	section 9.7
Λ	lambda	Sweepback ratio	degrees	section 9.3.4

Figure 9.2: Letters used in this Textbook

particular there must be no other change of energy (the fluid must not be flowing up or down hill, there must be no change of temperature or volume of the fluid, etc.). As described in chapter 4, a parcel of air that moves to an area of lower pressure expands and cools. Such changes make Bernoulli's Theorem invalid.

The effect of Bernoulli's Theorem is felt in several places within an aircraft:

- The pressure above a moving wing *is* less than the pressure below—see section 9.4.1 on page 176—and this *does* provide some element of lift: depending on the shape of wing, approximately 5% of the total lift may come from the drop in pressure of the air caused by it speeding up as it flows over the top of the wing.

- It is used on older aircraft to create a vacuum to turn the gyros in the heading and attitude indicators. In these aircraft a device looking rather like a warning horn from a vintage car is fitted to the outside of the aircraft, often in front of the passenger door; see figure 9.4. As the aircraft moves, air is forced through a constriction. This causes it to speed up and, by Bernoulli's principle, for its pressure to drop. This drop in pressure pulls air through the heading and attitude indicators, turning their gyros.

- The same effect applies in an engine's carburetor. Air is forced through a constriction and therefore speeds up. As it speeds up, its pressure drops and fuel is sucked into the airstream.

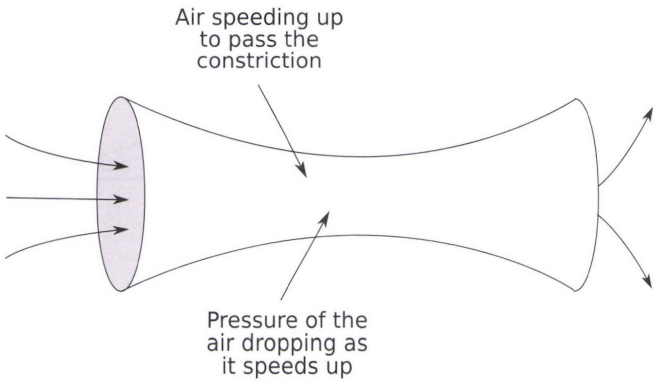

Figure 9.3: Bernoulli's Principle

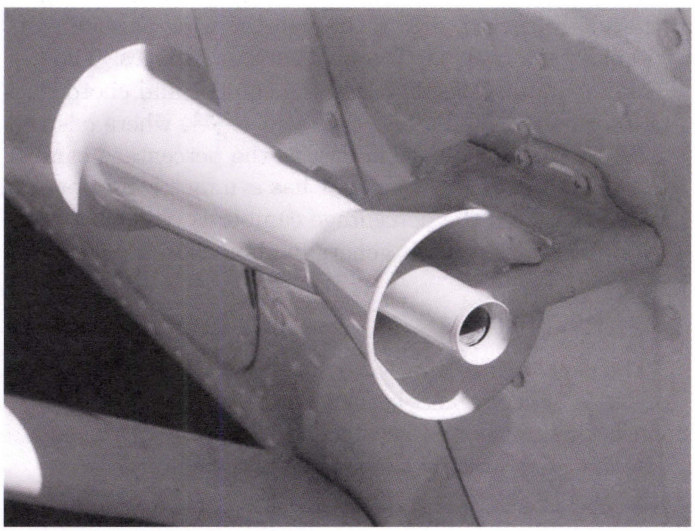

Figure 9.4: Vacuum Generation

Note that we also associate a drop in temperature with a drop in pressure (that is how carburetor icing occurs), but this has nothing to do with Bernoulli's Theorem.

To illustrate the principle of Bernoulli's Theorem yourself, try holding two sheets of paper in front of your mouth, about 1 cm apart and blow between them. Rather than moving apart as might be expected, the pieces of paper come together because of the reduced pressure between them.

9.2.6 Relative Airflow & Angle of Attack

As an aircraft flies, air flows over the wing. The direction that the air appears to be coming from depends on many factors. Imagine that you are blindfolded and strapped to the surface of the wing of an aerobatic aircraft. The aircraft goes into a vertical dive and you are asked where you feel the wind coming from: your answer would be "from straight ahead".

The angle between the chord of the wing and the direction from which the wind appears to be coming is called the *Angle of Attack* (AoA). In the case of the aircraft in a vertical dive, the AoA will be quite small.

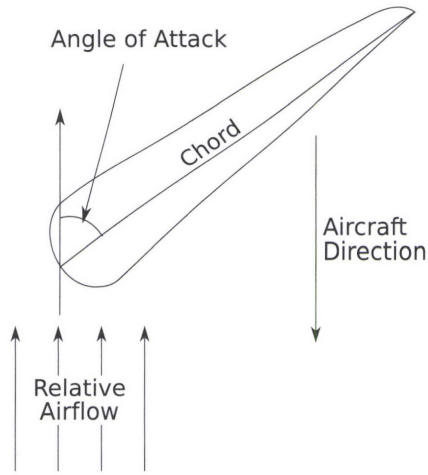

Figure 9.5: How to Stall at 200 knots

However, what if the pilot, realising that she is approaching the ground too quickly, pulls back firmly on the control column? The situation shown in figure 9.5 may occur: the aircraft is still moving downward (because of its inertia—Newton's First Law of Motion) but the wing has started to rotate towards the horizontal. If the pilot has pulled back very hard, the AoA could now become large.

An aircraft stalls when the AoA passes a certain value (typically between 15° and 20° in a light aircraft). The aircraft in figure 9.5 may therefore be travelling at 200 knots or more and still be stalled.

9.2.7 Further Reading

There are numerous books available for studying the theory of flight. For those readers with basic calculus skills, *Aerodynamics for Engineering Students*[2] by Houghton and Carpenter provides a thorough but not intimidating book on the subject. Unlike some of the older text books, it uses scientific rather than Imperial units.

For those without a calculus background, *Piloting for Maximum Performance*[3] by Lewis Bjork includes not only some of the theory associated with aerofoils but also some practical experiments you can perform in an aircraft to measure certain characteristics.

9.3 Design of the Wing

A wing is just one example of the aerofoils present on an aircraft (see section 9.4). The wing is studied in some

[2]ISBN 0-7506-5111-3.
[3]ISBN 0-07-005699-4.

depth in this section and the terminology required for aerofoils in general (e.g., camber, chord) is introduced.

9.3.1 Aerofoil Terminology

Wing Planform

The term *planform* is used to describe the overall shape of a wing from wingtip to wingtip. If you imagine the sun to be directly overhead, then the planform is the shape of the shadow of the whole wing (including the notional part inside the fuselage) projected onto the ground.

Wing Area

The area of a wing is the area of its planform—the area of its shadow on the ground when the sun is directly overhead. This includes that part of the wing that lies inside the fuselage. In the formulæ in this chapter, the term *wing area* means exactly this, and is not a measure of the amount of metal or fibre-glass used in the construction of the wing.

Wing Loading

Wing loading gives a measure of how much work a wing has to do to keep the aircraft in flight: how much lift each square metre of wing needs to provide. It is found by dividing the weight of the aircraft (in newtons) by the area of wing (in square metres).

For a Cessna 150 at maximum gross weight, the wing loading is approximately 500 newtons per square metre (about 10.4 lbs-force per square foot); for a Boeing 747 it is about 7,300 newtons per square metre (about 152 lbs-force per square foot).

Wing Span

The span of a wing is the maximum distance between the two wingtips.

Wing Chord

The chord at a position on a wing is the length of a line, normally inside the wing, drawn from the back of the trailing edge to the front of the leading edge—see figure 9.6.

Unless the wing's planform is completely rectangular, its chord will vary at different points along it. When comparing wings of different aircraft, the *mean aerodynamic chord* is used. This is the chord of an equivalent rectangular wing with the same area and position of centre of pressure at a given AoA. The mean aerodynamic chord therefore changes (slightly) depending on the AoA.

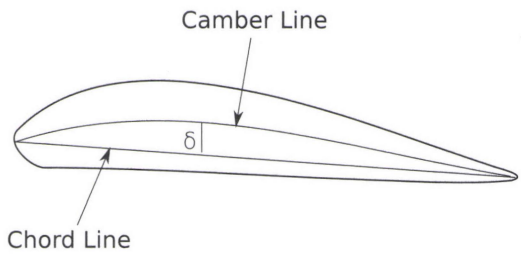

Figure 9.6: Cross-section of a Wing

Wing Camber

As illustrated in figure 9.6, the camber of a wing is a measure of its cross-section. The *camber line* is a line, normally curved, drawn through the wing at each point equidistant from the top and bottom surfaces. The maximum distance between the camber and chord lines is normally called δ and the ratio $\frac{100\times\delta}{c}$, where c is the length of the chord, is known as the percentage camber of the wing. For a wing that has symmetrical upper and lower surfaces the percentage camber is obviously zero. Its maximum value is generally about 5%.

Aspect Ratio

The aspect ratio of a wing is a dimensionless number (i.e., it is the same whether you are using Imperial or scientific units) and is calculated by dividing the square of the wing span by the area of the wing.

Aircraft Type	Aspect Ratio
Concorde	1.85
Piper Archer	5.6
Piper Cherokee PA-180	6.0
Boeing 747-100	7.0
Cessna 172	7.32
Boeing 747-400	8.0
King Air	9.8
Competition gliders	≈30

Figure 9.7: Aspect Ratios of Common Aircraft

This is illustrated in figure 9.8 which compares the aspect ratios of two simplified (rectangular) wings of the same area. Both wings have an area of 16 square units but Wing B has four times the aspect ratio of Wing A. Figure 9.7 gives the aspect ratios for some well-known types of aircraft.

A high aspect ratio indicates a long, narrow wing, and a low aspect ratio indicate a short, stubby wing.

One of the important characteristics of a wing with high aspect ratio is its reduced induced drag; see section 9.3.13. Of course, aircraft are not the only things that need efficient wings: birds such as albatrosses that cover

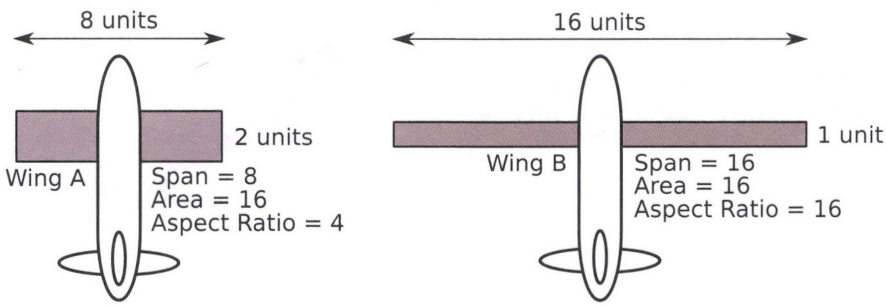

Figure 9.8: Aspect Ratio of a Wing

long distances on migratory routes also have wings with high aspect ratios.

9.3.2 Characterising Aerofoils

The *National Advisory Committee for Aeronautics* (NACA), the precursor to the *National Aeronautics and Space Administration* (NASA) in the USA devised a system of digits to describe an aerofoil. The simplest form requires four digits following the acronym NACA:

- The first digit is 100 times the percentage camber (see page 170)
- The second digit is 10 times the position of the maximum camber as a fraction of the wing measured back from the leading edge
- The last two digits are 100 times the maximum thickness of the aerofoil as a percentage of the chord.

Exercise 65 *A wing is described as being NACA 4412. What does this mean?*

Possible answers to the exercises are given at the end of the chapter, starting on page 197.

Exercise 66 *What does it mean if the first two digits of a NACA description of an aerofoil are both zero?*

Given the NACA numbering of an aerofoil, many of its flight characteristics can be deduced. While it is not required for the Transport Canada written examination, it might be interesting to note that the equation for the surface of a NACA-00xx (i.e., symmetric) aerofoil is given by:

$$y = 5 \times c \times t \times \left[\left(0.2969 \times \sqrt{\frac{x}{c}} \right) - \left(0.1260 \times \frac{x}{c} \right) - \left(0.3517 \times \left(\frac{x}{c} \right)^2 \right) + \left(0.2843 \times \left(\frac{x}{c} \right)^3 \right) - \left(0.1015 \times \left(\frac{x}{c} \right)^4 \right) \right]$$

where y is the height of the wing surface above the chord, c is the chord of the wing, t is the camber (the last two digits of the NACA number divided by 100) and x is the distance across the wing from the leading edge ($x = 0$) to the trailing edge ($x = c$).

In addition to the four-digit numbering, NACA also defined 5, 6, 7 and 8 digit numbering to give a more complete description of an aerofoil.

9.3.3 Laminar Flow

Loosely speaking, laminar flow is smooth, non-turbulent flow of air over an aerofoil.

To be more specific, consider the surface of an aerofoil. Next to the surface there will be a *boundary layer* of air that is not moving with respect to the aerofoil—it is in contact with the aerofoil and moving with it. If your car has leaves and dust on it when it starts moving, the leaves will blow away, but the dust will not. The dust particles are so small that they are in the boundary layer: the air around them is moving with the car and so there is no air flow to blow them away.

However, a long way from the aerofoil, the air is moving with respect to the aerofoil. The question is, how does the transition occur between the stationary air of the boundary layer and moving air? If the layers of air flow smoothly across each other without passing energy between them, then the flow is said to be *laminar*. If not, it is turbulent.

Some aerofoils, known as *laminar flow aerofoils* are specifically designed to maintain laminar flow. Other methods of maintaining laminar flow are discussed in section 9.3.10 on page 174.

9.3.4 Sweepback

Sweepback is one of the mechanisms for improving the lateral (roll) stability of an aircraft—see section 9.8.2 on page 194.

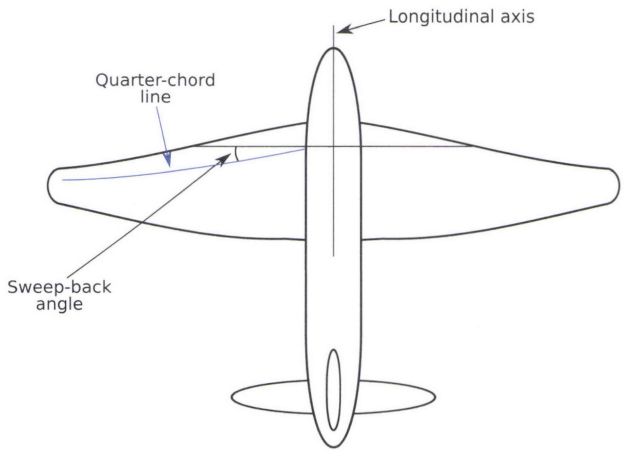

Figure 9.9: Sweepback

Sweepback is an angle calculated as follows (see figure 9.9):

- draw a line through the wing planform joining points at a given percentage of the chord. Typically the value used is either a quarter of the chord or the leading edge.
- draw a line perpendicular to the longitudinal axis of the aircraft.
- measure the acute angle between these lines—this is the sweepback angle. It is normally designated by Λ_{LE} if the leading edge is used or $\Lambda_{\frac{1}{4}}$ if the quarter chord line is used.

9.3.5 Dihedral/Anhedral

If you look at an aircraft from directly in front, the angle that the wings or elevator make with the horizontal is called the dihedral (if the wings are shaped upward towards the tips) or anhedral (if the wings droop downward towards the tips).

On some aircraft the wing is constructed in sections, angled differently: see figure 9.10. These are known as polyhedral wings, and winglets (see section 9.3.13) are one form of this. Polyhedral wings are popular for competition gliders.

The primary purpose of dihedral wings is to increase lateral (roll) stability (see section 9.8.2)—a characteristic described by Sir George Cayley in 1808.[4]

[4]Sir George described the lifting characteristics of an aerofoil in 1792: see Richard Dee's book *The Man who Discovered Flight: George Cayley and the First Airplane* ISBN 978-0771029714.

Figure 9.10: Polyhedral Wings on a Model Glider

9.3.6 Wash In/Wash Out

The angle between the chord line of a wing and the longitudinal axis of the fuselage is known as the *angle of incidence*. Normally each side of the wing is built slightly twisted so that the angle of incidence changes between the root (fuselage attachment point) and the tip.

If the angle of incidence increases towards the tip then the wing is said to have *wash-in* and if the angle of incidence decreases towards the tip then the wing is said to have *wash-out*.

Wash-out is typically used on a light aircraft so that the angle of attack (see section 9.2.6) when the aircraft is flying is greater at the wing root than at the wingtip. This means that the root of the wing will generally stall before the tips, allowing aileron control to be effective for longer.

9.3.7 Slots/Slats

In the early days of aviation, Sir Frederick Handley Page in Britain and Gustav Lachmann in Germany[5] noticed that various species of bird have a small group of feathers, known as the alula, attached to their thumb bone. They deploy these in front of the wing when flying slowly, leaving a gap between them and the leading edge known as a *slot*—see figure 9.12.

Slots are also created at the trailing edge of the wing when flaps are deployed—see section 9.3.9.

The actual mechanism by which slots in the wing improve low speed flight is another common fallacy in the Theory of Flight. It is generally believed that the purpose of the slots is to introduce high energy air from the bottom of the wing to the top to prevent stagnation in the boundary layer—see the description of vortex generators in section 9.3.10. The father of aerodynamics, Ludwig Prandtl, started this idea in the early part of the 20th century and it persisted until the 1990s when detailed measurements proved that it was incorrect. It is salutary to think that, for the best part of a century,

[5]A First World War fighter pilot.

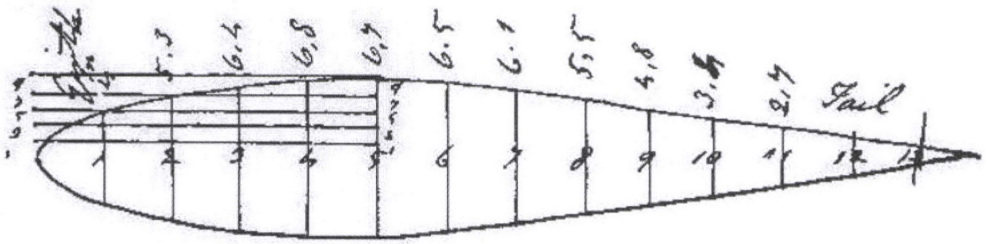

Figure 9.11: One of Sir George Cayley's Aerofoil Designs (1804)

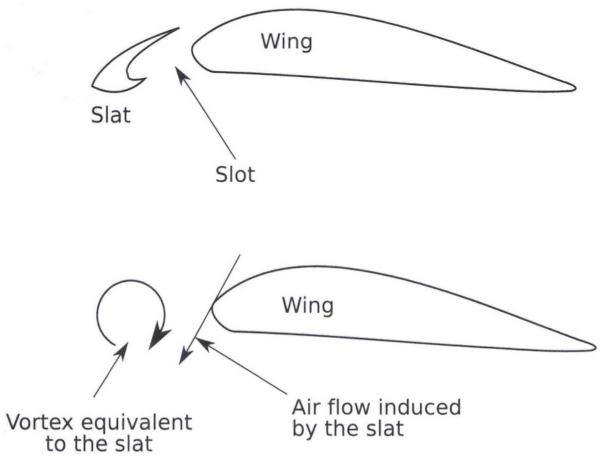

Figure 9.12: Leading Edge Slat

aircraft were being fitted with a device critical for slow-speed flying for entirely the wrong reason!

It is now believed that the effect of a slat in front of the leading edge is equivalent to a vortex as illustrated in the lower part of figure 9.12. This vortex induces air to flow from the top surface of the wing to the bottom causing a drop in pressure on the top surface and a rise in pressure on the bottom. This has the effect of slightly increasing the coefficient of lift, C_L.

9.3.8 Spoilers

A spoiler is a plate that can be raised into the airflow on top of a wing to destroy lift. Although spoilers can have a braking effect, they are different from air brakes in that they are designed to destroy lift in a controlled manner while producing as little drag as possible. By contrast, air brakes (which are much less common on aircraft) are specifically designed to create drag.

Airliners are normally fitted with spoilers (figure 9.13 shows the spoilers on an Airbus A321) to increase the rate of descent without a significant increase in speed. They are used by gliders for the same reason.

Airliners also use spoilers to bank in high speed flight, working with the ailerons and destroying part of the lift on one wing. On some aircraft with high aspect ratio wings, such as the Mitsubishi MU-2, the flaps take up most of the trailing edge of the wing and there is no room for ailerons. So on MU-2s, all banking is induced by spoilers. This makes crosswind landings challenging.

Once on the ground, an airliner will typically deploy its spoilers fully (see figure 9.13), partly to increase the drag to slow the aircraft down, but primarily to destroy the lift of the wing and place more weight on the landing gear to help braking.

Figure 9.13: Spoilers Deployed on an Airbus A321

9.3.9 Flaps

As shown in figure 9.15, trailing edge flaps of various types are used to increase the camber of the wing, the angle of incidence of the wing and the area of the wing (see figure 9.14) to improve the low-speed performance of the aircraft. Equation 9.3 on page 180 describes the amount of lift produced by a wing. It can be seen from that equation that increasing the coefficient of lift (C_L) by changing the camber and increasing the area (A) both contribute to creating additional lift. The types of flap include:

- The **plain flap** that rotates on a simple hinge.

- The **split flap** where the top of the wing remains unchanged when the flap extends.
- The **Fowler flap,** invented by Harlan D. Fowler in 1927, which slides backwards before hinging downward, thereby increasing both camber and chord.
- The **slotted flap** which opens a slot between the flap and the wing, allowing air from below the wing to move to the top and re-energise the boundary layer over the flap. This helps the airflow to stay attached to the flap, delaying the stall.

As well as improving the low-speed performance, extending flaps also increases drag and causes the nose to pitch down. This helps during landing because it helps to slow the aircraft and gives the pilot a better view over the nose of the aircraft.

Flap Type	Camber	Angle of Incidence	Area
Plain Flap	Increases	Increases	
Fowler Flap	Increases	Increases	Increases
Split Flap	Increases	Increases	
Slotted Flap	Increases	Increases	Increases

Figure 9.14: The Characteristics of some Common Flaps

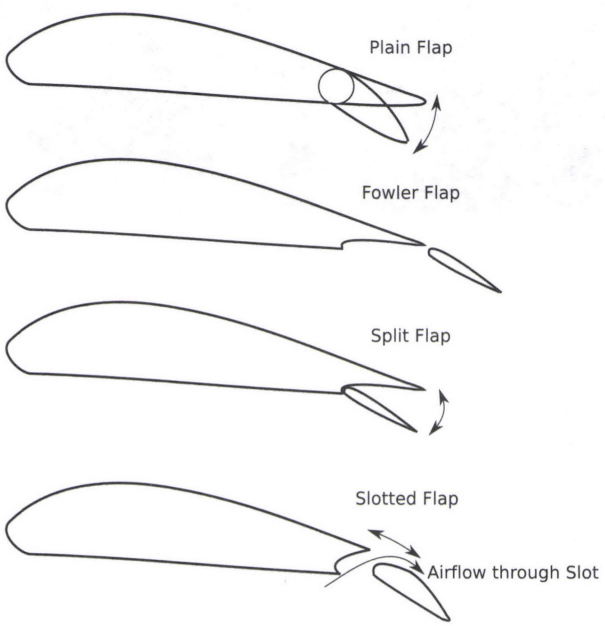

Figure 9.15: Some Common Types of Simple Flaps

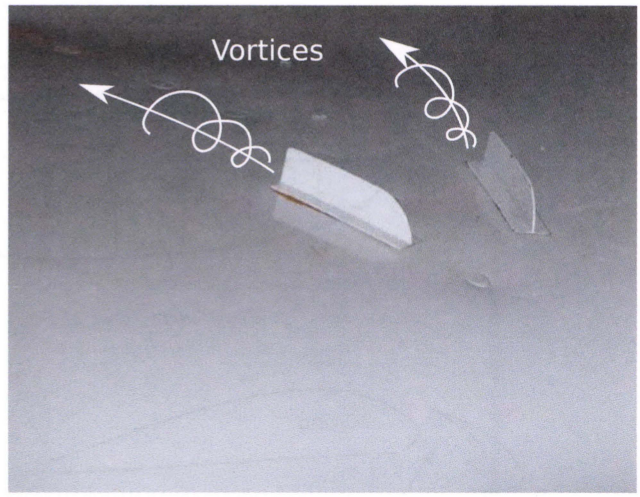

Figure 9.16: Vortex Generators on a Cessna 182 Wing

9.3.10 Vortex Generators

Vortex generators are controlled irregularities in the upper surface of a wing. They prevent the air from flowing smoothly over the wing and cause vortices to form. This may be considered undesirable: certainly they add to the parasitic drag and, given the attention normally made to ensuring smooth airflow across the wing, deliberately causing roughness would seem to be counter-productive.

However, the idea is to *prevent* the flow of air from separating from the upper surface of the wing, particularly at low speeds, using a technique devised as long ago as 1904 by Ludwig Prandtl. Prandtl showed that at low speeds, the air close to the surface of the wing becomes "tired" (his term). This layer of low-energy air close to the surface encourages the main flow to separate from the top of the wing, causing a stall. The two basic techniques to cure this problem are either to remove this tired air (by letting it escape through a slot in the wing) or to re-energise it. Vortex generators (see figure 9.16) are one way of re-energising it, others include directing a small portion of the output from a jet engine to the wing (this is used on the Antonov An 72/74 transport aircraft), blowing jets of air out of holes on the upper surface of the wing or allowing fresh air from below the wing to travel to the upper surface in front of a trailing edge flap.

In general, vortex generators reduce the stall speed of an aircraft by re-energising the boundary-layer air and keeping the main flow of air in contact with the upper surface of the wing at slower speeds (higher angles of attack). They are typically used in Short Takeoff and Landing (STOL) aircraft.

Other ways of generating vortices include wing fences and saw-tooth leading edges.

9.3.11 Wing Fences

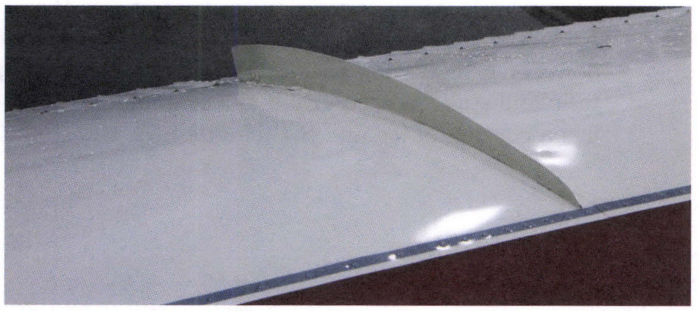

Figure 9.17: Wing Fence on a Cessna 172 (C W Clark)

Wing fences are, eponymously, fences raised above the top surface of the wing running backwards from the leading edge as shown in figure 9.17. Wing fences have two primary purposes: they are extremely good vortex generators (see section 9.3.10) and they act as a barrier to air moving towards the tip of the wing. Both of these improve the performance of the wing at high angles of attack.

Vortilons are wing fences designed to have effect only at very high angles of attack: see, for example, the devices fitted under the leading edges of the wing in figure 9.18.

Figure 9.18: Vortilons (James Redmon)

9.3.12 Stall Strips

Stall strips consist of small irregularities fitted to the leading edge of a wing, usually near the wing root. They disturb the air flow at high angles of attack and thereby cause the wing root to stall before the tips, leading to a more controlled stall characteristic. In this respect they have the same effect as wash-out (section 9.3.6).

Figure 9.19 shows the stall strip on the wing of the American Aviation AA-1 Yankee.

Figure 9.19: Stall Strip

9.3.13 Winglets

Equation 9.7 on page 183 describes induced drag as follows (symbols are as in figure 9.2 on page 168):

$$D_i = \frac{4 \times k \times L^2}{\pi \times r \times \rho \times v^2 \times A} \tag{9.1}$$

One important term in the equation is r, the aspect ratio of the wing. This appears on the bottom line of the drag equation so the larger it can be made, the more the induced drag will be reduced. An infinitely long wing would have no induced drag at all!

In practice it is, of course, impractical to build commercial aircraft wings with very large aspect ratios because of the need to maintain the strength of the wing. Adding a winglet to the tip of the wing has the advantage of reducing the induced drag without actually increasing the aspect ratio. Data from the Boeing 747-400 indicates that winglets reduce drag by about 2.5%, corresponding to a weight saving of about 9.5 tons at takeoff. Figure 9.20 shows the winglets on a Rutan VariEze: a homebuilt aircraft.

A winglet works by reducing the tendency for air to flow around the tips of the wing from the underneath to the relatively lower-pressure top surface, causing wing-tip vortices.

9.3.14 Canards

Canard is the French word for "duck" and is the term used for a wing mounted on an aircraft in front of the main wing as in figure 9.20. Normally it refers to a moveable aerofoil rather like an elevator fitted to the front of the aircraft. The main advantages of a canard rather than a conventional stabiliser/elevator are as follows.

Figure 9.20: Winglets & Canards (Adrian Pingstone)

- For stability, the horizontal tail of an aircraft is normally fitted to give negative lift—see the upper part of figure 9.21. This is somewhat inefficient, and a canard can provide the same stability while producing positive lift—see the lower part of that figure.

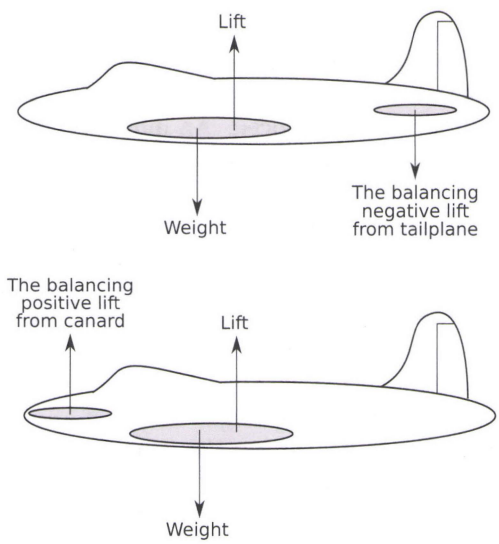

Figure 9.21: Tailplane and Canard

- The stall characteristics of a canard can be set so that, in level flight, it will stall before the main wing. The effect of it stalling is to pitch the nose of the aircraft down, thus decreasing the AoA on the main wing. In contrast, a tailplane stall can be very dangerous and difficult to recover from. As figure 9.21 indicates, the stall of either a tailplane or a canard will cause a nose-down pitching moment. The tailplane stall is more serious because the nose-down moment increases the angle of attack on the tailplane (making the stall more severe) whereas it reduces the AoA on the canard (making the stall less severe). Another mechanism that causes the AoA on a tailplane to increase is putting the flaps down on a high-wing aircraft: this can also trigger a tailplane stall, particularly if the tailplane already has a coating of ice and is therefore near the stall.

9.4 Aerofoils

There are many aerofoils on a general aviation aircraft including the wings, the vertical tail, the horizontal tail and the propeller blades. Much of the terminology described in section 9.3 for the wing is actually applicable to any aerofoil. An aerofoil is a shape that generally has a rounded leading edge, a thickness that increases smoothly to some maximum (usually between 25% and 50% of the way towards the back of the wing) and then smoothly tapers off to the trailing edge.

Subject to certain conditions, as an aerofoil moves through the air it deflects the air and, by Newton's third law, experiences a force. This force may act upward (e.g., lift from wings), may act sideways (e.g., from the vertical tail), may act downward (e.g., from the horizontal tail) or forwards (e.g., from a propeller). The actual mechanism by which an aerofoil creates lift is described in section 9.5.1.

9.4.1 Pressure Distribution

This section deals with the general pressure distribution around a wing in flight and defines two special pressure-related points: the *aerodynamic centre* of the wing and its *centre of pressure*. Here a wing is used as an example of an aerofoil; any of the other aerofoils on the aircraft could have been used.

General Pressure Distribution

As a wing moves through the air it disturbs the air and, in accordance with Bernoulli's theorem, the pressure of the air around it changes. The point made repeatedly in this chapter is that the Bernoulli-induced pressure differences on the top and bottom are not the major cause of lift from a wing, but it is true that the pressures both above and below a moving wing *are* lower than that of the atmosphere and the air pressure below the wing is higher than that on top. This is caused by the downward flow of air across the wing.

The pressure across the surface of a moving aerofoil changes with the AoA of the wing (the angle at which the wing meets the airflow—see section 9.2.6). Figure 9.22 illustrates typical patterns. The arrows are

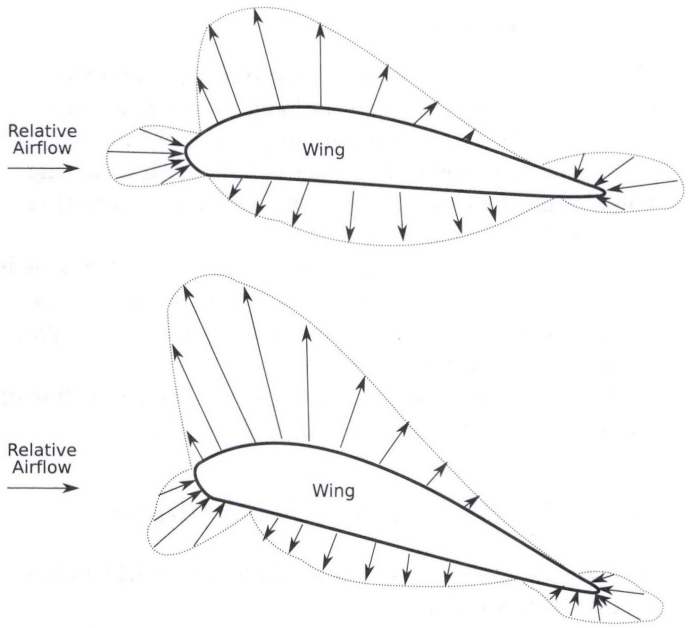

Figure 9.22: Pressure Around a Wing

measures of the dimensionless *coefficient of pressure* defined by

$$C_p = \frac{p - p_\infty}{\frac{1}{2} \times \rho \times v^2} \tag{9.2}$$

where p is the pressure at a point on the wing, p_∞ (pressure at infinity) is the pressure a long way in front of the wing (before it is disturbed by the approaching wing), and the other symbols are as in figure 9.2 on page 168.

The length of the arrows in figure 9.22 are measures of C_p at that point and their directions indicate whether C_p is positive (the local pressure is greater than the surrounding air and the arrows point towards the wing) or negative (the local pressure is less than the surrounding air and the arrows point away from the wing). The interesting point to note is that, under normal flying conditions, the pressure below the wing *and* the pressure above the wing are both lower than the pressure of the surrounding air—illustrated by the arrows pointing away from the wing. The pressure above the wing is, however, lower than the pressure under the wing—illustrated by the longer arrows on the top surface.

As the AoA increases (see lower part of figure 9.22), the pressure on the top of the wing drops further and a pressure higher than that of the surrounding air may build up underneath the leading edge, contributing to lift.

Aerodynamic Centre

As can be seen from the arrows in figure 9.22, the forces acting on a wing in flight are complex and change with the angle of attack. Most of these forces not only tend to cause the wing to lift or drop, they also cause it to rotate about the lateral axis (i.e., cause the aircraft's nose to pitch up or down).

If this rotational tendency is plotted for each point along a chord of the wing it is generally found that the pattern moves as the AoA changes. However, at one point on the chord, the rotational tendency is unchanged for reasonable angles of attack (say up to 10°). This point is known as the *aerodynamic centre* of the wing. It is normally close to the chord line about 23% to 25% of the way back from the leading edge.

Centre of Pressure (C of P)

Lift occurs at most points of a non-stalled wing. But, for each angle of attack, there is one point where the lift force has no tendency to cause rotation. For the purposes of calculation, these individual lifting forces are combined into one force that is assumed to act at that point, called the *centre of pressure*.[6]

When calculating the effects of lift on a wing it is sometimes simpler to assume that all of the lift and drag act at the aerodynamic centre and there is no rotational effect. In other calculations, because, for normal flight attitudes the aerodynamic centre doesn't move, it is simpler to assume that lift, drag and rotational effect occur there.

The centre of pressure, in contrast, moves as the AoA changes. For a symmetric aerofoil the centre of pressure typically lies about 25% of the chord length behind the leading edge and moves little as the angle of attack changes. On a normal aerofoil, however, the centre of pressure typically lies a little behind the quarter-chord point at large AoA, but as the AoA reduces, the centre of pressure moves toward the trailing edge.

Exercise 67 *The pilot of a Cessna 172 in straight and level flight at 100 knots inadvertently induces a stall by reducing speed while attempting to maintain altitude. Describe the changes in the position of the centre of pressure as the stall is approached and reached.*

9.4.2 Downwash

A wing can be considered as a device for causing air to be deflected downward: thus generating an upward

[6] This is analogous to pretending that all the weight is situated at the Centre of Gravity.

force, called lift. This downward motion of the air is known as *downwash* or *induced velocity.*

9.4.3 Wingtip/Trailing Vortices

Trailing vortices are one of the consequences of downwash and of the pressure being lower above a wing than beneath it.

As can be seen from figure 9.22, the air above the wing is generally at a pressure lower than that below the wing. The upper and lower surfaces meet at the trailing edge and at the wingtips and there can be no pressure difference there. There is therefore a tendency on the upper surface of the wing for air to flow from the tip towards the root (i.e., the fuselage), being replaced by air from beneath. Underneath the wing, air will tend to flow inwards to a lesser extent or even to flow outwards. Where these two flows meet at the trailing edge of the wing the difference in their directions and speeds causes the air to rotate and form vortices: see figure 9.23.

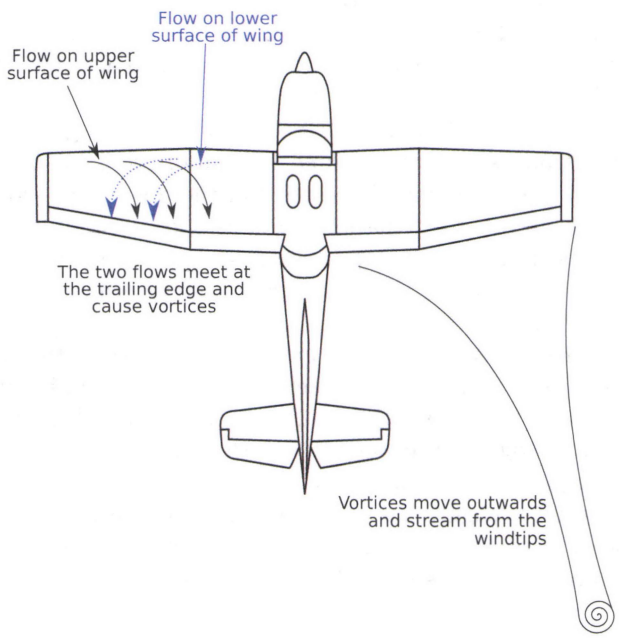

Figure 9.23: The Generation of Trailing Vortices

These vortices form at all points along the trailing edge but roll up into two large vortices just inboard of each wingtip—forming wingtip vortices behind and below each wingtip.

These vortices are rotating and the air in them, therefore, has more energy than the still air from which it was formed. Since energy cannot be created from nothing, work has to be done (and energy lost) by the aircraft, and this is seen as extra drag, a phenomenon known as *Induced Drag*, see page 182.

9.4.4 Angle of Incidence

The angle between the chord line of a wing and the centre line of the fuselage (its longitudinal axis—see section 9.8.1) is known as the *angle of incidence.* Normally each side of the wing is built with a varying angle of incidence (i.e., the wing is slightly twisted) as described in section 9.3.6.

An aircraft is normally designed so that, when it is in straight and level cruise flight, its longitudinal axis is horizontal and the angle of incidence is therefore equal to the angle of attack.

Putting flaps down on a wing alters the chord line of the wing and therefore the angle of incidence.

9.5 Forces on an Aeroplane

If might be useful to review sections 3.8 to 3.11 before reading this section.

When an aircraft is flying, there are four major forces acting on it (see figure 9.24):

1. Lift—the force that prevents the aircraft falling to the ground; see section 9.5.1
2. Weight—the force that counteracts the lift, preventing the aircraft from rising to the stratosphere; see section 9.5.2
3. Thrust—the force that makes the aircraft move forward through the air; see section 9.5.3
4. Drag—the force that holds the aircraft back; see section 9.5.4

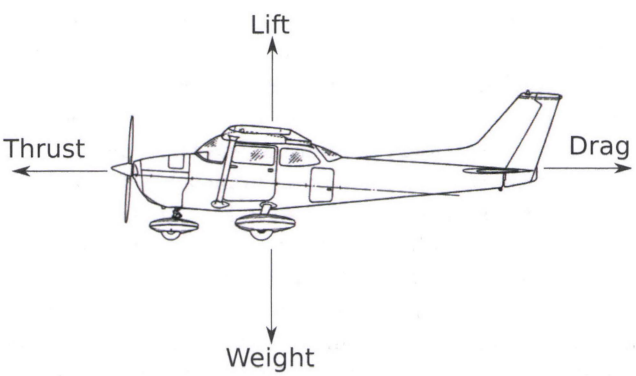

Figure 9.24: The Four Forces

Exercise 68 *An aircraft is travelling at 100 knots (51.5 metres/sec) in level flight. If its thrust is equal to its drag and its lift is equal to its weight, what will happen to it?*

Exercise 69 *An aircraft is travelling at 100 knots (51.5 metres/sec). If its thrust is equal to its drag but the pilot adjusts the lift to be greater than the weight, what will happen to it?*

Exercise 70 *If an aircraft is flying through the air in such a condition that its thrust is less than its drag and its lift is less than its weight, then what is happening to it?*

Exercise 71 *For a glider, the thrust is zero. How can it fly?*

9.5.1 Lift

An aircraft creates lift by exploiting Newton's third law of motion. In the same way that a canoe is propelled forwards when the paddle pushes water backwards, so a wing is lifted when it pushes air downward. The wing applies a force to the air to force it downward and, by Newton's third law, an equal and opposite force acts on the wing pushing it upward.

The first point to be made about lift is that it does not need an aerofoil (the shape of a wing) to create it. If you sit in the passenger seat of a moving car and hold your hand or a sheet of plywood out of the window so that it deflects air downward (figure 9.25), then you will feel it lifting. The primary difference between the sheet

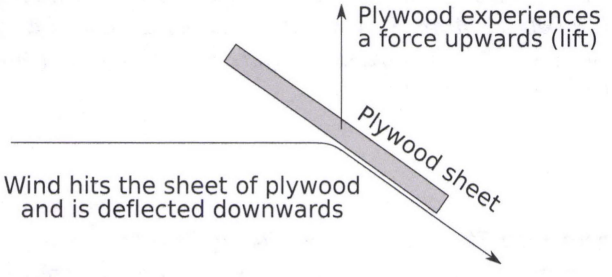

Figure 9.25: Plywood held out of a Car Window

of plywood and an aerofoil is what happens to the air passing over the upper surface. In the case of the plywood it will become turbulent and create a significant amount of drag. In the case of an aerofoil such as a wing, the air passing both sides of the aerofoil is deflected downward until a certain critical angle is reached between the aerofoil and the wind—see figure 9.26.

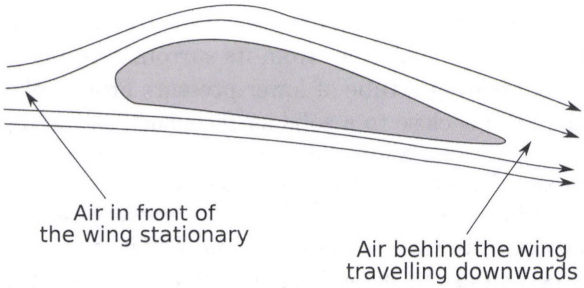

Figure 9.26: An Aerofoil Passing through the Air

One obvious question is, "why should the air follow the top of the wing, and not simply stream out horizontally as shown in figure 9.27?"

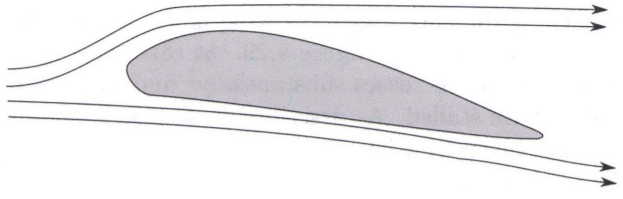

Figure 9.27: Without the Coandă Effect

The answer to this question is named the *Coandă* Effect (pronounced "Kwanduh") after Henri Coandă who first realised how it could be applied to an aircraft wing. It was first described by Thomas Young in 1800.

A common demonstration of the Coandă Effect is to direct the outflow from a vacuum cleaner vertically upwards and balance a table-tennis ball in the airflow. This is expected: the upward flow of the air is balancing the weight of the ball. But if the air stream is moved away from the vertical, the ball still remains balanced; see figure 9.28! There are many demonstrations of this on YouTube (but there are also demonstrations of water from a tap following the back of a spoon and this is not caused by the Coandă Effect).

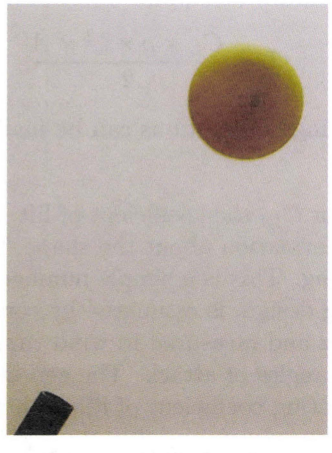

Figure 9.28: The Coandă Effect

What is actually happening is that the jet of moving air pulls in air molecules from its surroundings as it passes, creating a tube of lower pressure around the jet. If the tube is close to a solid surface, such as the top of a wing (or a table-tennis ball), then a low pressure forms between the jet and the surface because air cannot be sucked in from that side. The lower pressure causes the jet to bend towards the surface and follow it.

As long as the air adheres to the top of the wing through the Coandă Effect, as the angle between the aerofoil and the wind (the "angle of attack"—see section 9.2.6 on page 169) increases, the amount of air deflected downward increases and so the lift increases.

There comes a point, however, when the aerofoil is making such an angle with the oncoming air that the air cannot follow the top surface and detaches itself, creating turbulence above the wing much as with the sheet of plywood—see figure 9.29. At this point the amount of lift decreases substantially[7] and the aerofoil is said to have stalled. As described in section 9.2.6, a stall does not occur at a particular airspeed—it occurs when the angle between the wing and the relative air flow exceeds a particular value.

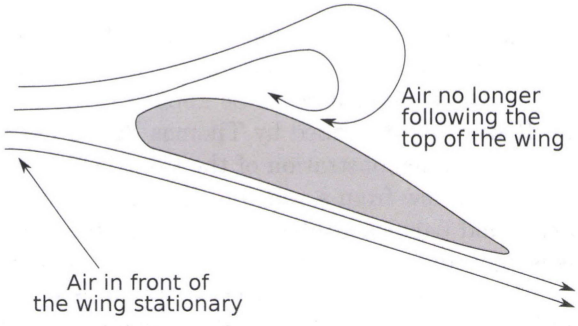

Figure 9.29: A Stall

The lift being created by an aerofoil passing through the air can be calculated by using the following formula (symbols are as listed in figure 9.2 on page 168):

$$L = \frac{C_L \times \rho \times v^2 \times A}{2} \tag{9.3}$$

Some interesting observations can be made about this equation:

- The factor C_L, the coefficient of lift, incorporates all of the information about the shape, thickness, etc. of the wing. This is a simple number that, for each new wing design, is estimated by computer modelling and measured in wind tunnel tests for different angles of attack. The general shape of the curve relating coefficient of lift with AoA is illustrated in figure 9.30 using figures for a Boeing 747-200—the coefficient of lift increases more-or-less linearly as the AoA increases. At some AoA the wing will stall and the lift decrease rapidly.
- The lift increases as the square of the speed of the aircraft. This means that, everything else being equal, if the speed of the aircraft doubles, four times as much lift is generated.

It is sometimes stated that the coefficient of lift cannot be greater than 1. This is not true: some modern designs of wings have coefficients of lift as large as 10.

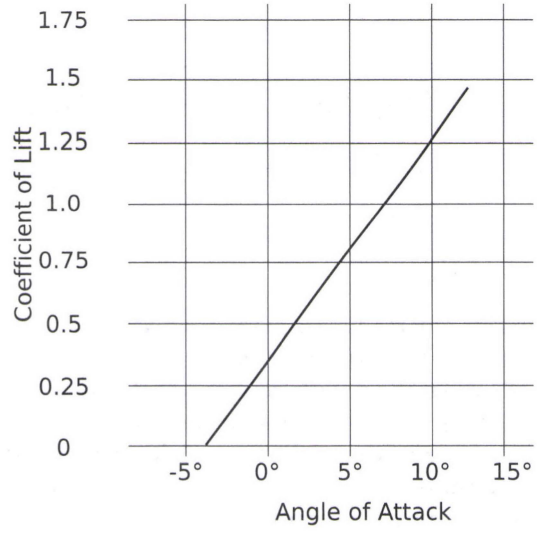

Figure 9.30: Coefficient of Lift .v. AoA for B747-200

Exercise 72 *The curve given in figure 9.30 is valid for a Boeing 747-200. Such an aircraft is flying at 265.5 metres per second (516 knots) at 12,192 metres (40,000 ft) at an AoA of 2.4°. The wing area of a Boeing 747-200 is given in figure 9.1. How much lift is the wing generating?*

Exercise 73 *Consider the Boeing 747-200 cruising as in example 72. Had the gross weight of the aircraft been 2,366,000 newtons (531,898 lbs-force), then at what AoA would the pilot need to fly straight and level?*

Exercises 72 and 73 demonstrate that reducing the weight of an aircraft means that less lift is required and the AoA for level flight can then be smaller.

While addressing the subject of lift, it may be useful to point out that one explanation of lift given in some

[7] In the worst case the only lift being created may be coming from the high-pressure region under the leading edge (see figure 9.22).

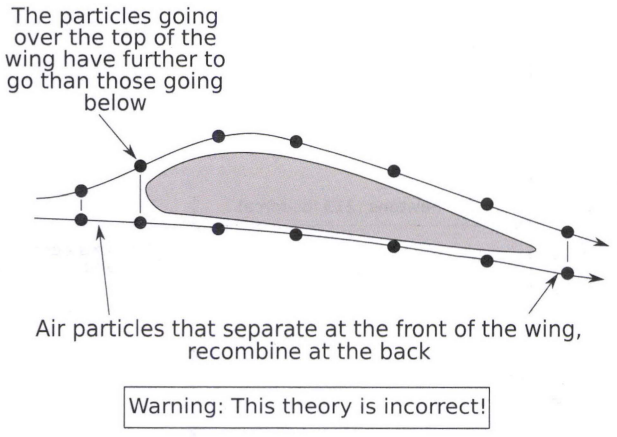

Figure 9.31: The Equal Time Fallacy

flying texts (although not in any aerodynamics texts) is wrong. The "explanation" goes as follows: Consider the wing in figure 9.31 and two particles of air that are together at the leading edge of the wing. If one particle goes above the wing and the other below then, since they must meet up again at the trailing edge,[8] the particle following the upper surface of the wing must have travelled a greater distance and must therefore have moved faster. Moving faster causes a lower pressure and therefore the wing is sucked upward into the lower pressure above. A moment's thought reveals many fallacies in this argument (how could an aircraft fly upside down, what about the lift generated from the flat sheet of plywood in figure 9.25, etc.?) but it is curiously persistent in aviation circles.

NASA has an interesting webpage at `https://www.grc.nasa.gov/WWW/k-12/airplane/wrong1.html` that describes the "equal time" idea in detail. The page is headed "Incorrect Theory #1".

9.5.2 Weight

The weight of an aircraft, measured in newtons or pounds-force, consists of the individual weights of many parts (the airframe, the fuel, the passengers, etc.). For the purposes of calculations all of these weights are combined and are assumed to act at one point: the *centre of mass* or *centre of gravity*.[9] The centre of gravity is the point at which the aircraft could be balanced on a finger (or, more realistically, on a pivot).

It is essential for a safe flight that both the total weight of the aircraft and the position of its centre of gravity be within the limits prescribed by the manufacturer. For details of how to perform this calculation see section 11.6 on page 247.

[8] That's the fallacy: it is never explained why they must meet up again at the trailing edge (and, in fact, they don't)!

[9] On the earth, where gravity is constant, these two terms mean the same thing.

9.5.3 Thrust

Thrust is created by the aircraft's engines through Newton's third law of motion (see page 167). In this way it is similar to lift: to create lift, the wings force air downwards and so the aircraft goes upwards; to create thrust, the engines force air backwards and the aircraft therefore moves forward.

The main types of engines used in aircraft are described in sections 12.3 (page 264) and 12.4. In summary:

- Propeller-driven aircraft use a rotating aerofoil to drive air backwards. This is the same generation of force as happens when a wing moves through the air to generate lift. In the case of a propeller, the aerofoil is placed on its side and is rotated, forcing air backwards.
- Jet aircraft also force air backwards, ejecting it from the jet engine.
- Rocket engines do not force air backwards (and will therefore work in a vacuum), but instead eject material previously stored on board backwards at high speed.

In each case, thrust is generated by the reaction described in Newton's third law. In particular, it is *not* caused by the substance forced backwards pushing on the air behind the aircraft.

After landing, it is useful to deploy reverse thrust (i.e., thrust backwards) to slow the aircraft more quickly; see section 12.6 on page 280.

9.5.4 Drag

Any body moving through a fluid (a liquid or gas) experiences drag: a force acting in the opposite direction to its motion. Drag on an aircraft in flight can be categorised as shown in figure 9.32. There are three primary causes: parasitic (sometimes incorrectly called "parasite"), induced and wave drag. These are discussed in the following sections.

Parasitic Drag

This type of drag is what is commonly thought of as "air resistance". Each aircraft has a particular shape that is more or less "aerodynamic". If you imagine the difference between thrusting a pointed knife blade and a flat plate into a viscous liquid such as molasses you will understand the concept of parasitic drag: the knife will pass into the liquid with less drag because it is more

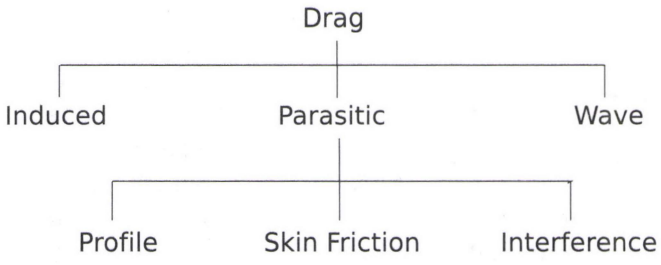

Figure 9.32: Types of Drag

streamlined. This type of drag depends on the shape of the aircraft (whether it's streamlined or not), the density of the air and the speed at which it is travelling. The formula used to calculate parasitic drag is:

$$Dp = C_{Dp} \times A \times \rho \times v^2 \tag{9.4}$$

where the symbols are as in figure 9.2 on page 168.[10]

The coefficient of parasitic drag, C_{Dp}, is a dimensionless number specific to a particular aircraft. It defines "how streamlined" the aircraft is. For a Cessna 172, for example, C_{Dp} is about 0.018 and for a Boeing 747, about 0.011 (the smaller the better). The important point to note about C_{Dp} is that, until the aircraft approaches the speed of sound or a stalling condition (where the coefficient of lift starts to drop), its value doesn't change very much. The equivalent value for induced drag (see below) changes dramatically as the speed of the aircraft changes.

Because the speed is squared in formula 9.4, if the speed of an aircraft doubles, the parasitic drag increases by a factor of four. Figure 9.33 illustrates the parasitic drag curve for a Cessna 172 with $C_{Dp} = 0.018$ travelling through standard density air.

Exercise 74 *The Cessna 172 whose parasitic drag characteristic is illustrated in figure 9.33 is flying at 51.5 metres per second (100 knots) in straight and level flight. How much thrust is required in this situation to overcome parasitic drag?*

Parasitic drag actually has three components as shown in figure 9.32:

1. **Profile drag** (also called *form drag* or *pressure drag*). This is determined by the shape of the aircraft: how streamlined it is. Aircraft with a larger cross-sections generally have a higher drag.

2. **Skin friction.** This arises from the friction of the air against the "skin" of the aircraft in the boundary layer around the aircraft. Skin friction can be reduced by using smooth laminar-flow wings (see section 9.3.3), ensuring that the aircraft is kept clean and polished, and designing the fuselage to have an optimal "fineness" ratio. The fineness ratio is the ratio of the aircraft's fuselage length to width. For minimum skin friction an almost "egg-shaped" fuselage (as on the Questair Venture) is optimal.

3. **Interference drag.** This drag arises from vortices other than those caused by lift—see induced drag below. When two surfaces meet at a sharp angle on an aircraft, the air flowing over them forms a vortex. Making the air accelerate into this vortex requires work and therefore causes drag on the aircraft. It is to reduce this type of drag that fairings[11] are fitted to aircraft, for example where the wing struts meet the fuselage and wings. Glider pilots carefully tape up joints between wings and fuselage to reduce this type of drag when taking part in competitions.

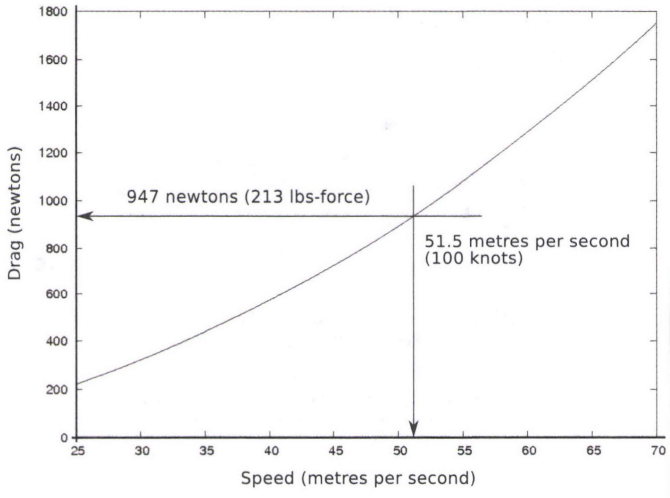

Figure 9.33: Parasitic Drag for Example 74

Induced Drag

Induced drag is drag caused by lift. If the AoA of an aircraft is zero then the aircraft is producing no lift and there is no induced drag. However, to remain flying, an aircraft has to produce lift and so the pilot sets the AoA at something larger than zero and induced drag results.

As described in section 9.4.3, wingtip vortices are an unavoidable byproduct of creating lift with an aerofoil. The energy that goes into producing these appears to the aircraft as induced drag.

This simple description is true, but figure 9.34 provides a more thorough explanation (beyond that

[10] In some texts, equation 9.4 has a 2 on the bottom line. This is simply a different way of defining the drag coefficient.

[11] Sheets of plastic or metal used at the junction of two parts of the aircraft to "smooth" the corner.

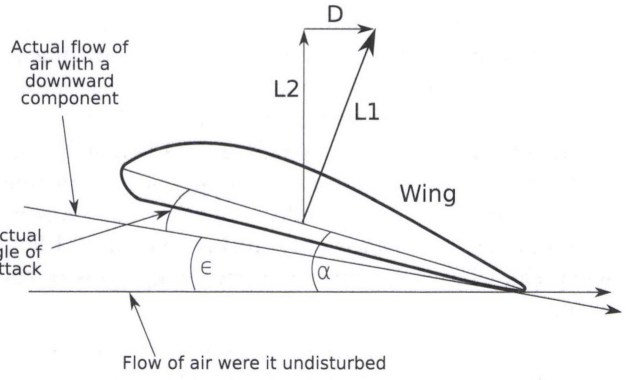

Figure 9.34: The Cause of Induced Drag

needed for the Transport Canada examination). The calculations of lift performed earlier assumed that the airflow arriving at a wing when the aircraft is in level flight is effectively horizontal: see the upper part of figure 9.35. The angle of incidence of the wing is then the same as its AoA. In fact, the air arriving at the leading edge of the wing is already moving downward slightly, being affected by the air in front of it, as shown in the lower part of figure 9.35. The AoA is therefore not as great as would be supposed. In figure 9.34 the AoA of the wing could be assumed to be α whereas, because of the downward motion of the oncoming air, it is only $\alpha - \epsilon$. With a smaller AoA, the lift is obviously less and additional work has to be done to create sufficient lift. The additional force that is needed to do this work is represented by $\vec{D}$ in figure 9.34: the difference between the lift that would have been needed had the air been moving horizontally and the lift that is actually needed. $\vec{D}$ is a force acting towards the rear of the aircraft—it acts as drag.

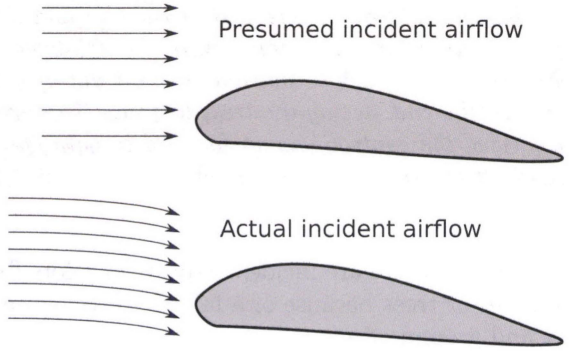

Figure 9.35: Air Striking the Front of the Wing

In this way induced drag is caused by the downwash of the air as it passes over the wing: i.e., from the act of creating lift.

The equation used to calculate induced drag is superficially identical to that for parasitic drag (equation 9.4) but with a different coefficient:

$$D_i = C_{Di} \times A \times \rho \times v^2 \tag{9.5}$$

where the symbols are as in figure 9.2 on page 168.

Your first reaction to this equation may be that it must be wrong. It is well known that induced drag *decreases* with speed and yet equation 9.5 implies that it *increases* with the square of the speed (v). The solution is hidden within the coefficient of induced drag, C_{Di}. This differs from the coefficient of parasitic drag in one very important way: it is not constant and depends on the coefficient of lift (see section 9.5.1):

$$C_{Di} = \frac{k \times C_L^2}{\pi \times r} \tag{9.6}$$

where r is the aspect ratio of the wing and k is a constant determined by the shape of the wing. For a perfectly elliptical wing[12] $k = 1.0$. For most wings, k lies between 1.05 and 1.15.

Combining equations 9.3 (which defines C_L) and equation 9.6 (which defines C_{Di}) with equation 9.5, the complete equation for induced drag becomes:

$$\begin{aligned} D_i &= C_{Di} \times A \times \rho \times v^2 \\ &= \frac{k \times C_L^2}{\pi \times r} \times A \times \rho \times v^2 \\ &= \frac{k}{\pi \times r} \times \left(\frac{2 \times L}{\rho \times v^2 \times A} \right)^2 \times A \times \rho \times v^2 \\ &= \frac{4 \times k \times L^2}{\pi \times r \times \rho \times v^2 \times A} \end{aligned} \tag{9.7}$$

This fits in with our preconceived notion that the induced drag should decrease when the speed increases—in fact, with a v^2 on the bottom line, it quarters if the speed doubles, if everything else remains the same. It also indicates that induced drag will be less for wings with larger aspect ratios (r is on the bottom line). Simulating a large aspect ratio is one of the purposes of adding winglets to aircraft, see section 9.3.13.

One particular circumstance for induced drag occurs when the aircraft is in straight and level flight. When this occurs the lift required is equal to the weight of the aircraft. As equation 9.7 shows, in this circumstance the induced drag varies as the square of the aircraft's weight. Double the weight of the aircraft and the induced drag increases four-fold.

[12] An elliptical wing is one where the leading and trailing edges are segments of ellipses. The wing on the Supermarine Spitfire was close to being elliptical.

Exercise 75 *A Cessna 172 has $k = 1.1$ and an aspect ratio of 7.32 (see figure 9.7 on page 170). Assume that it is loaded to 10,231 newtons (2,300 lbs-force) and is flying in straight and level flight through air with a density of 1.225 kg per cubic metre at 51.5 metres per second (100 knots). How much induced drag does it experience?*

Exercises 74 and 75 show that, for a Cessna 172 moving at 100 knots, the induced drag is much less than the parasitic drag.

Using the values from exercise 75, figure 9.36 plots the induced drag for a Cessna 172 at various speeds.

As can be seen from equation 9.7, the greatest induced drag occurs for a heavy aircraft (where L is large) with short fat wings (where r is small) travelling slowly (where v is small).

Wave Drag

Wave drag occurs when an aircraft is moving close to or beyond the speed of sound. Effectively a wall of air builds up in front of the aircraft and shock waves are formed. As with wing-tip vortices, these dissipate energy, and their generation therefore appears as drag.

You may think that most light, general-aviation aircraft are unlikely to experience wave drag at the speed they fly, but even a Cessna 172 has one part moving at close to the speed of sound—the tips of the propellers. The tip of a Cessna 172's propeller travels 5.98 metres at each rotation. At 2,500 rpm such a tip is travelling at 898 km/hr. The speed of sound is approximately $331.4 + 0.6T_c$ metres per second where T_c is the air temperature in degrees Celsius. Thus, at 15° C the speed of sound is approximately 1,225 km/hr. The propeller tip is therefore moving at approximately 73% of the speed of sound (i.e., Mach 0.73). Shock waves typically start to form at around Mach 0.8 so even with a Cessna 172 propeller there is the possibility of wave drag on the propeller tips.

Furthermore, even when the aircraft is flying well below the speed of sound, local airflow over irregularities in the aircraft's skin can accelerate to supersonic speeds.

9.5.5 Ground Effect

When an aircraft is very close to the ground, the wingtip vortices cannot form completely, and the induced drag is less: a phenomenon known as *ground effect*. Although the mathematics is too complex to be included here, it can be shown that an aircraft weighing 220,000 newtons (about 49,500 lbs-force) with a wingspan of 27.4 metres (about 90 ft) flying at 45 metres per second (about 90 knots) experiences a reduction in drag as shown in figure 9.37. At a height of 15.2 metres (55% of the wingspan) the reduction in drag is about 1,390 newtons (about 312 lbs-force). As can be seen from figure 9.37, this reduction in drag is lost quickly as the height increases.

Some aircraft, known as ekranoplans, are specifically designed to fly in ground effect, but, for most aircraft, ground effect is a factor only during takeoff and landing, when the wing is within one or two wingspans of the ground.

The reduced drag when an aircraft is in ground effect can have both positive and negative effects:

- It can allow an aircraft taking off from a rough field to get airborne before true flying speed has been reached. True flying speed can then be built while the aircraft is in ground effect. However, if the pilot attempts to pull the aircraft out of ground effect prematurely, the aircraft will be unable to climb. This is a common cause of accidents.
- If it is not anticipated during a landing, ground effect can cause the aircraft to float down the runway and potentially to run off the departure end.[13]

Anecdote 26 *I was once a front-seat passenger in a 4-seater aircraft taking off from a grass strip with trees at the end of the runway. The pilot, seeing the trees ahead, pulled back hard on the control column during the ground roll and managed to get the (low-wing) aircraft off the ground quite quickly. With the reduced drag of ground effect, the aircraft started to climb away but, as it moved out of ground effect, the drag increased and the aircraft dropped back. The pilot was puzzled and checked the throttle was pushed right in and the flaps in their normal position. All of the available power was not enough to pull the aircraft out of ground effect. In the end, seeing the trees looming, I intervened and pushed the control column forward to gain speed in ground effect before starting the climb.*

Every year there are incident reports of pilots flying into fences or trees because of a failure to recognise slow flight and ground effect.

Total Drag

The total drag that an aircraft experiences as it flies can be found by adding up the three different types of drag.

[13] Note that this is not the same effect as approaching a hot runway and being caught in the warm, rising air: this can also cause the aircraft to float but is not an example of ground effect.

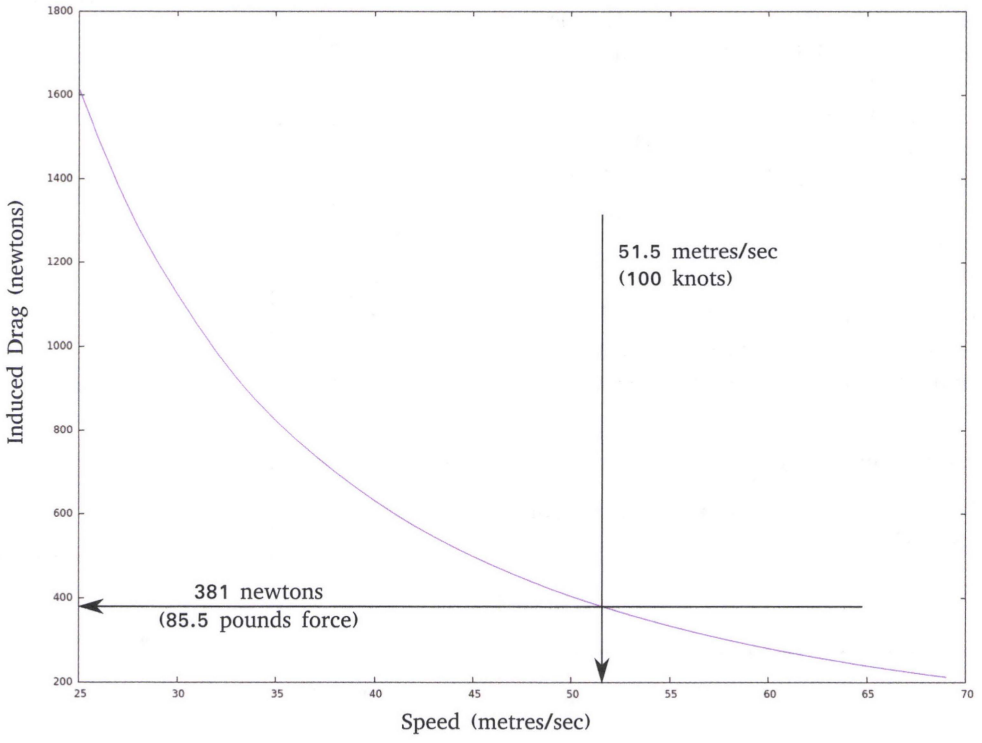

Figure 9.36: Induced Drag on a Cessna 172

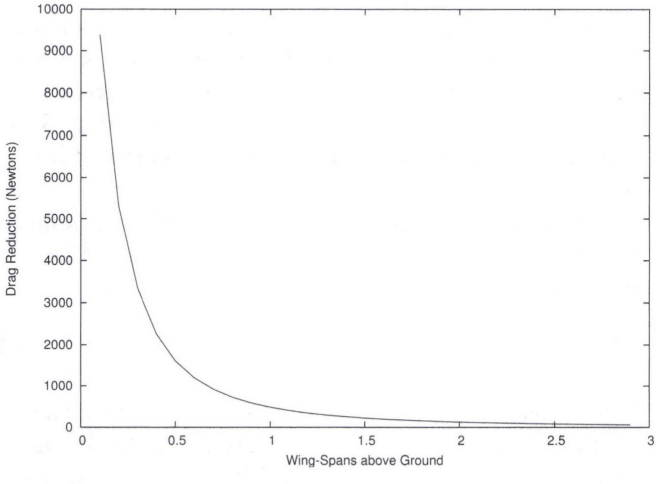

Figure 9.37: Reduction in Drag while in Ground Effect

At slow speeds, wave drag is very small and the total drag is effectively the sum of the induced and parasitic drag.

Equation 9.4 shows that parasitic drag is *directly* proportional to the square of the speed and equation 9.5 shows that *induced* drag is inversely proportional to the square of the speed. Simple calculus then indicates that the total drag curve will have a minimum value and that this will occur where the two lines cross over. Figure 9.38 illustrates this for our Cessna 172-like aircraft by combining the curves in figures 9.33 and 9.36.

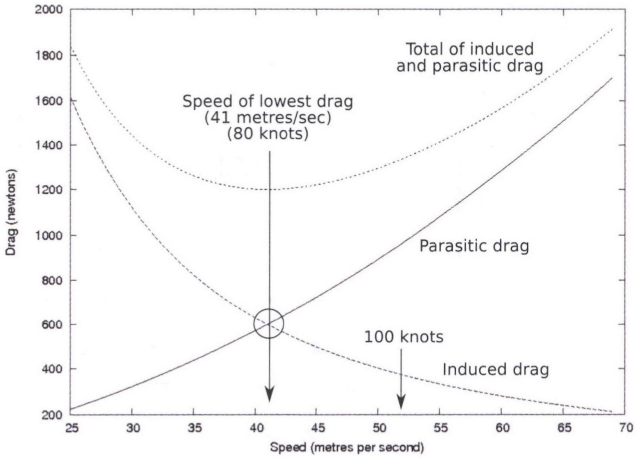

Figure 9.38: Total Drag on a Cessna 172

9.5.6 Lift/Drag Ratio

Up to the point of stalling, the lift being created by a wing can be increased by increasing the AoA. Unfortunately, increasing the AoA also increases drag.

The lift and drag of a wing depend on:

- the AoA and shape of the airfoil. These together define its coefficients of lift (C_L) and drag (C_D).

The general shape of the C_L curve for a fictitious aircraft is given in figure 9.39. This is a simplified curve and, in reality, C_L depends on factors other than the AoA—e.g., Mach number and amount of turbulence. In figure 9.39 it can be seen that the lift is at a maximum at an AoA of about 17°. That angle is then the AoA at which the wing will stall. Figure 9.30 shows the actual curve for a Boeing 747-200.

Figure 9.40 illustrates the general shape of the drag coefficient against AoA. As expected, the drag increases dramatically with increased angles of attack.

- the plan area of the airfoil: A
- the square of the speed at which the wing is moving through the air—v^2
- the density of the air: ρ

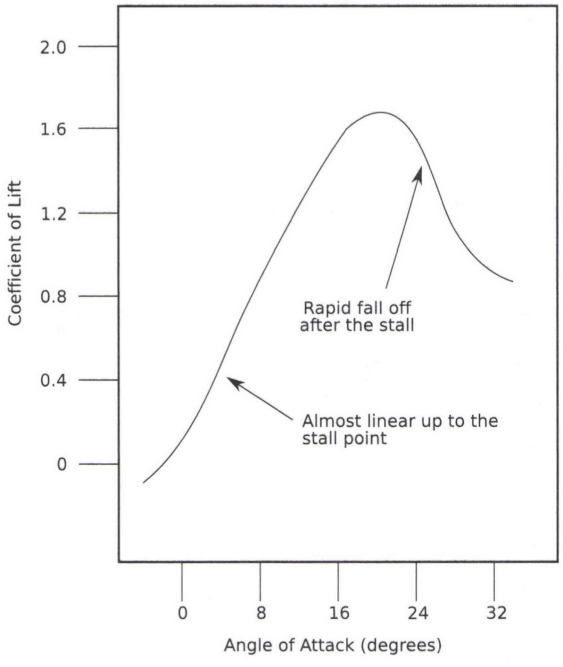

Figure 9.39: Coefficient of Lift for a Fictitious Aircraft

The ratio $\frac{C_L}{C_D}$ is known as the Lift/Drag Ratio. This reaches its peak at higher angles of attack for high-aspect wings (e.g., gliders) than for stubby wings. Typical lift/drag ratios are approximately 7 for a Cessna 152 in level cruise, 60 for a modern single-seater glider, between 14 and 17 for an Airbus in cruise and 12 for a Boeing 767-200 acting as a glider into Gimli.[14]

[14]This is a reference to July 1983 event where an Air Canada 767-200 ran out of fuel at 41,000 ft about halfway through its flight from Montréal to Edmonton. The crew was able to glide the aircraft safely to a landing at the Industrial Park Airport at Gimli, Manitoba.

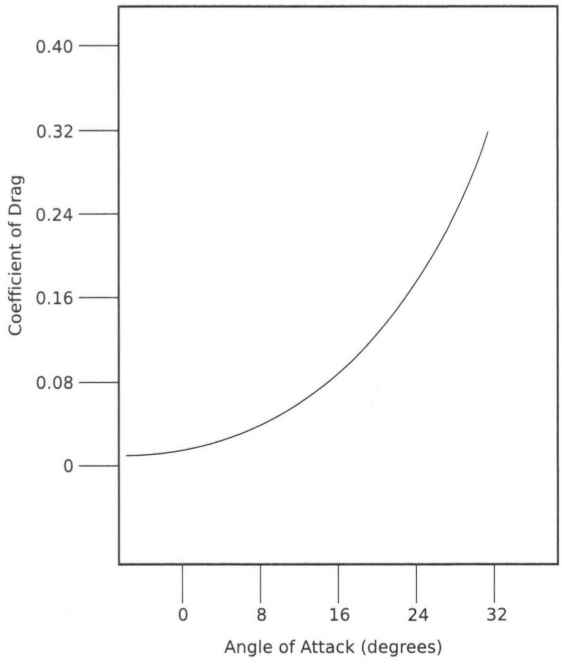

Figure 9.40: Coefficient of Drag for a Fictitious Aircraft

9.5.7 Relationship of Lift & Drag to Angle of Attack

As figure 9.30 illustrates, as the AoA increases, so does the amount of lift generated. The relationship is almost linear until the point at which the AoA is so great that the air flow breaks away from the top of the wing. When that occurs, the aerofoil stalls and the amount of lift decreases rapidly.

The relationship between the AoA and drag is more complex and is probably best seen in equation 9.7 on page 183:

$$D_i = \frac{4 \times k \times L^2}{\pi \times r \times \rho \times v^2 \times A} \tag{9.8}$$

This indicates that, at least to the point of stall, the induced drag increases as the square of the lift being generated (i.e., if twice as much lift is required, there is four times as much induced drag).

9.5.8 Stalls & Spins

In the Transport Canada syllabus for the Commercial Pilot written examination, the mechanisms of aircraft stalling and spinning appear in the Flight Operations section. Since stalling and spinning are characteristics of an aerofoil, and depend on the changes in the coefficients of lift and drag with AoA, these are topics that are better addressed here.

Stalls

A stall occurs when the aircraft's angle of attack exceeds a critical value and the wing stops producing sufficient lift to maintain flight.

The density ratio ($\sigma = \frac{\rho}{\rho_0}$) at a particular altitude is the air density at that altitude relative to that at sea level. As altitude increases, the density ratio decreases (i.e., the air becomes less dense). This means that at a higher altitude, an aircraft stalls at a higher true airspeed (TAS). The indicated airspeed (IAS) and calibrated airspeed (CAS) of the stall remain the same with increasing altitude, but the actual speed through the air (TAS) increases.

Spins

A spin is an aggravated stall with the aircraft descending in a corkscrew path. The actual motion of a spinning aircraft is very difficult to describe—the aircraft is simultaneously rotating about all three of its axes. The spin is also very difficult to analyse mathematically because the aircraft is at very high angles of attack (typically between 60° and 90°) and experiencing very large side-slips (above 25°) and yaw rates (above 50° per second). These are areas where classical aerodynamic theory breaks down.

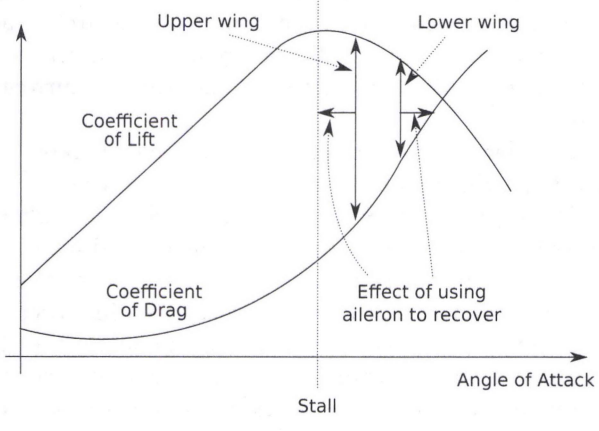

Figure 9.41: A Spin

A spin occurs when an aircraft stalls while it is yawing, causing the wing on one side of the aircraft to stall and the wing on the other side either not to stall or to stall less. Figure 9.41 illustrates the conditions of the two wings (assuming that the wing has stalled on both sides). The coefficient of lift curve is as in figure 9.30 on page 180, but this time it is taken out of its linear section past the AoA where the stall occurs. It can be seen from figure 9.41 that, in a spin, the upper wing (which is less severely stalled) is experiencing more lift than the lower wing and that the lower wing is experiencing more drag.

The motion resulting from this asymmetry is known as *autorotation* and occurs in three phases:

1. **The incipient spin.** This phase starts when the aircraft stalls and rotation around the longitudinal axis starts (i.e., a wing drops); it ends when the spin axis becomes vertical. In most light aircraft the incipient spin lasts about two turns with the nose often rising at the end of the first turn, thereby increasing the AoA and causing a deeper stall.

2. **The developed spin.** This starts when the spin axis is vertical and continues until recovery begins.

3. **The recovery.** This is normally initiated by the pilot stopping the rotation (the exact mechanism for this being aircraft-dependent) and then reducing the AoA of the wings by gradually raising the aircraft's nose.

Figure 9.41 explains why the rotation of a spin cannot be stopped by the use of ailerons. Assume that your aircraft is spinning to the left and you apply the control column to the right to try to recover, putting the right aileron up and the left aileron down. This increases the angle of attack on the left (lower) wing, moving the lower wing further to the right in figure 9.41. This reduces its lift even more while increasing its drag—making the situation worse. On the right (upper) wing, the situation is reversed: the AoA is lowered, moving the line to the left in figure 9.41. The result is to increase the asymmetry between the wings, encouraging the spin.

9.5.9 Spiral Dive

A spiral dive is a banked and descending turn where speed is increasing and radius of turn is possibly decreasing (often because of incorrect pilot action—trying to slow the aircraft by pulling back on the control column, causing the radius to reduce).

A spiral dive is particularly dangerous in an aircraft with neutral or negative directional and lateral stability (see section 9.8.2 on page 194). In such an aircraft a gust of wind may start a small roll, for example, to the right. A side-slip to the right results and this causes a yaw to the right. If the aircraft's stability is neutral or negative, then the aircraft keeps turning and the bank angle keeps increasing until a high-speed, spiral dive occurs.

A spiral dive differs from a spin because, in a spiral dive, neither wing is stalled. The recovery differs from aircraft to aircraft but typically involves reducing power, stopping the rotation with a co-ordinated turn and then bringing the nose of the aircraft up to the horizon and allowing the speed to reduce.

Generally, a spiral dive is more dangerous than a spin because:

- speed builds up rapidly
- the natural reaction of the pilot to an increase of speed, pulling the nose of the aircraft up, is precisely the wrong action in a spiral—it simply tightens the turn
- the load factor on the aircraft (see section 9.7 on page 192) during the recovery from the spiral dive can easily exceed the rated load factor of the aircraft, causing catastrophic in-air breakup of the aircraft

It is therefore important in a rotating aircraft, particularly when in IMC, to be able to distinguish quickly between a spin and a spiral dive from instruments alone. The primary instrument for distinguishing the two is the airspeed indicator—if the airspeed is increasing rapidly then the aircraft is almost certainly in a spiral dive.

Anecdote 27 *Spiral dives really happen. When I was a solo student working towards my private pilot licence, I was flying circuits at my home airport and found myself on downwind with several aircraft ahead of me. I decided (correctly) to leave the circuit and wait until things quietened down. I therefore flew* 360° *turns a little way north of the airport but was staring very intently out of the side window looking for the aircraft in the circuit. When I glanced back at the instruments and looked out of the front window, I found myself at the beginning of a spiral dive: the combination of* 360° *turns while not concentrating on holding altitude had been enough to initiate a spiral dive.*

9.5.10 Forces Acting During a Turn

Note: There is no such thing as "centrifugal force"—it simply does not exist.

You will find in section 4.6.4 on page 66 that, when a rotating co-ordinate system is used (e.g., the earth), the concept of an imaginary centrifugal force can be mathematically useful. This is not the case when considering the theory of flight.

Exam Hint 19 *For the purposes of passing a Transport Canada examination, you may need to pretend that Centrifugal Force exists, but do not let this confuse you outside the examination room. Even the Transport Canada examinations are now changing to accept its nonexistence so you will probably not meet the concept other than in older textbooks.*

The concept of centrifugal force appears to have entered folklore because people have confused the forces acting on a body moving in a circle. Think about driving a car along a straight road and then making a right turn. As the driver you follow the car to the right (or fall out!)—in which direction is the force acting on you and the car? The obvious and correct answer is: towards the centre of the circle. If the road is not covered with ice, you will feel the left-hand door of the car pushing on your left arm towards the centre of the circle. The wheels of your car are similarly being acted upon by a force pushing it towards the middle of the turn. This force is known as a *centripetal* force.

Had the car been on an icy road, the road would not have been able to apply an inward force to its wheels and the car, in accordance with Newton's first law of motion, would have continued in a straight line.

"Centrifugal" force is supposed to act on a body moving in a circle and somehow pull the body outward. That no such force exists is easy to see: imagine a boy rotating a stone on the end of a string around in a circle. The stone is receiving a force towards the centre of the circle (the centripetal force) from the string. If the string were to break (and the stone therefore no longer be subject to a force into the middle of the circle) then the stone would not fly off directly away from the centre but would continue in a straight line from its current position.

In order to turn, an aircraft banks and thereby directs part of its lift towards the centre of the circle—see figure 9.48 on page 192 which is simplified in figure 9.42. Note that there is an unbalanced force acting towards the centre of the turn and, since this force is unbalanced (there is no corresponding force acting outwards), the aircraft is not in equilibrium. In accordance with Newton's first law of motion, were the forces balanced, then the aircraft would continue in a straight line. That it does not continue in a straight line indicates that the forces are not balanced.

Intuitively you may realise that the faster the aircraft is flying, the more force is required to make it turn. Similarly, the tighter the required turn, the greater the force required. While it is not required for the Transport Canada examination, you may be interested to know the relationship between the force, the radius of the turn and the speed of the aircraft. It is:

$$F = \frac{W \times v^2}{g \times R} \tag{9.9}$$

where W is the weight of the aircraft, v its speed, R the

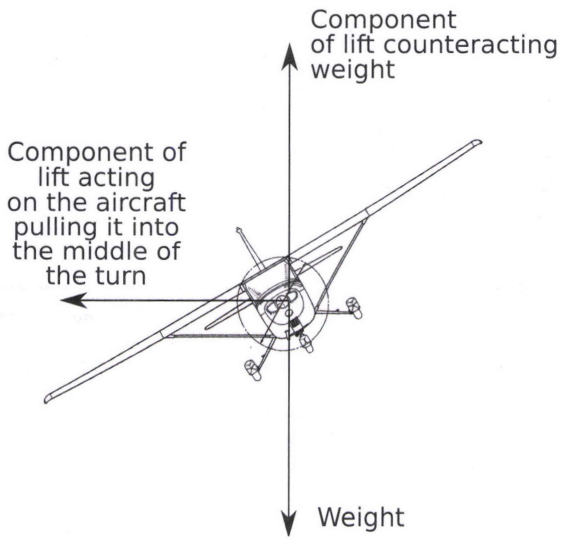

Figure 9.42: Forces Acting in a Turn

radius of the circle and g the acceleration due to gravity (about 9.81 metres per second per second).

Exercise 76 *An aircraft weighing 10,231 newtons (2,300 lbs-force) flying at 51.5 metres per second (100 knots) enters a rate one turn during which its altitude does not change. What is the radius of the turn and what angle of bank is required to make this turn?*

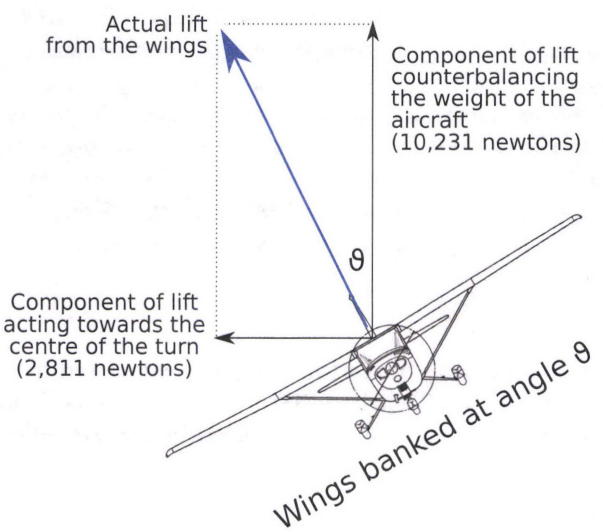

Figure 9.43: Diagram for Exercise 76

9.6 Propellers

Each propeller blade is an aerofoil and one can therefore speak about its chord and the other terms associated with an aerofoil. Its *blade angle* is the angle between the chord of the propeller aerofoil and the plane of rotation (90° to the crankshaft). A coarse-pitched propeller has a large blade angle and a fine-pitched propeller has a lower blade angle.

In practice, a propeller blade is washed-out (see section 9.3.6 on page 172) so that the blade angle changes between the root and the tip, with the tip being much finer than the root. This is because the tip is moving through the air much faster than the root and therefore does not need such a high AoA to create similar "lift" (i.e., thrust).

9.6.1 Fixed/Variable Pitch

A *variable-pitch propeller* (of which a constant speed propeller is one instance) is one where the blade angle can be changed. A *fixed-pitch propeller* is one where it cannot.

The pitch of a fixed-pitch propeller is a compromise between the fine pitch needed for climb and the coarse pitch needed for cruise. A variable pitch propeller has blades that can all be simultaneously rotated around their long axes to change their pitch. For some variable pitch propellers, the pitch angle can be set to zero or a negative value. When the pitch is set to 90° the propeller is said to be *feathered* and this is used to reduce drag if an engine fails. Negative pitch values can create reverse thrust for braking.

A *constant speed propeller* is a particular type of variable pitch propeller. A pilot flying an aircraft with constant speed propellers sets the required speed (rotations per minute) and the pitch of the blades automatically adjusts to maintain that speed—if, for example, the aircraft dives and speeds up and the propeller starts to over-speed, the pitch of the blades coarsens, thereby causing the propeller to slow down. Similarly, if the aircraft starts to climb and the propeller slows down, its pitch becomes finer and it therefore speeds up.

9.6.2 Blade Angle & Angle of Attack

When an aircraft is standing still (e.g., during the run-up with the pilot holding the brakes) the blade angle is clearly the same as the propeller aerofoil's AoA. As the aircraft starts to move through the air, this changes:

- If the propeller's blade angle remains unchanged, then as the aircraft's speed through the air increases, the propeller's AoA decreases. This means that the "lift" (i.e., thrust) produced by a propeller decreases as the aircraft's airspeed increases.

- As the propeller rotates more quickly at the same airspeed, the propeller's AoA increases (this is why a fast-rotating, fine-pitched propeller is used for climb).

In general, a propeller is more efficient for relatively slow airspeeds and a jet for higher ones. This is why turboprops (propellers turned by a gas turbine engine) are used in aircraft flying below about 400 knots.

9.6.3 Propeller Efficiency

Informally, the efficiency of a propeller is a measure of how much of the energy put into turning it appears as energy moving air backwards. More formally:

$$\eta = \frac{T \times v}{P_{\text{avail}}} \tag{9.10}$$

where P_{avail} is the power available from the engine and the other symbols are as described in figure 9.2 on page 168.

Equation 9.10 is correct, but is not of much use by itself because measuring the thrust (T) is extremely difficult. It depends on a number of factors including the airspeed of the aircraft and the speed at which the propeller is rotating. These two parameters are combined for convenience into a single factor known as the *Advance Ratio*. This is a dimensionless quantity defined by the equation:

$$J = \frac{v}{n \times D} \tag{9.11}$$

where v is the true airspeed of the aircraft, n is the speed of the propeller (revolutions per second[15]) and D is the diameter of the propeller.

Figure 9.44 illustrates the typical shape of the curve that associates a particular advance ratio with propeller efficiency. For a fixed-pitch propeller, one of the curves shown in figure 9.44 will apply and, for a particular number of propeller revolutions per second, there will be one airspeed at which the propeller is most efficient.

For a variable-pitch propeller, changing the pitch moves the maximum efficiency of the propeller to higher or lower airspeeds: this is the major advantage of such a propeller.

Figure 9.45 gives values for a McCauley 7557 propeller as is fitted on some Cessna 172s.

Equations 9.10 and 9.11 can be used, with information from the Pilot Operating Handbook, to find the thrust being produced by a propeller at a particular airspeed and revolutions per second. This is illustrated in the following exercise which is beyond the knowledge required for the Transport Canada written examination.

[15]Note: in order to keep the units consistent, this is *not* revolutions per *minute!*

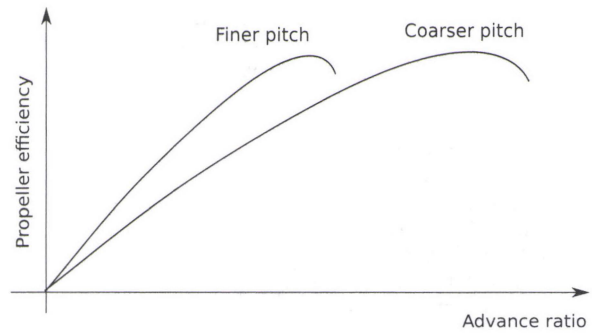

Figure 9.44: Propeller Efficiency against Advance Ratio

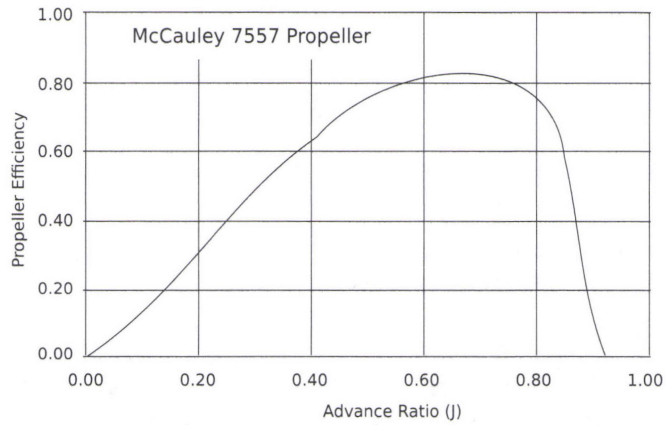

Figure 9.45: Efficiency .v. Advance Ratio

Exercise 77 *A single-engined light aircraft is fitted with a McCauley 7557 propeller with characteristics as shown in figure 9.45. The diameter of the propeller is 75 inches. According to the Pilot Operating Handbook, when the aircraft is flying at maximum gross weight at 8,000 ft pressure altitude at 2500 rpm the engine is providing 112 kW (about 150 HP) and the aircraft is moving at 109 knots. How much thrust is being produced?*

It is reassuring to see that the drag calculated in examples 74 and 75 (947 + 381 = 1,328 newtons) is less than the thrust that can be produced by the propeller.

9.6.4 The Power Curve

Section 3.11 on page 52 describes the concept of *power*. As an engine moves the aircraft forward, it does work against the drag. When the aircraft is in straight and level flight at a constant speed, the force being applied as thrust is equal to the drag. The thrust therefore changes, depending on the speed of the aircraft in accordance with the total drag as shown in figure 9.38. When a force moves something, it does *work* and the

rate at which work is being done is known as *power*. In this case, the power is:

$$P = D \times \frac{s}{t} = D \times v \tag{9.12}$$

where D is the total drag, s is the distance covered in time t, and v is the speed. This equation shows that the power required by the engine to sustain straight and level flight is proportional to the total drag times the speed of the aircraft. Figure 9.46 illustrates the power curve for the aircraft whose total drag is shown in figure 9.38. The power curve has the same general shape as the total drag curve, but its minimum value occurs at a lower speed: about 31 metres per second (60 knots) rather than 41 metres per second (80 knots).

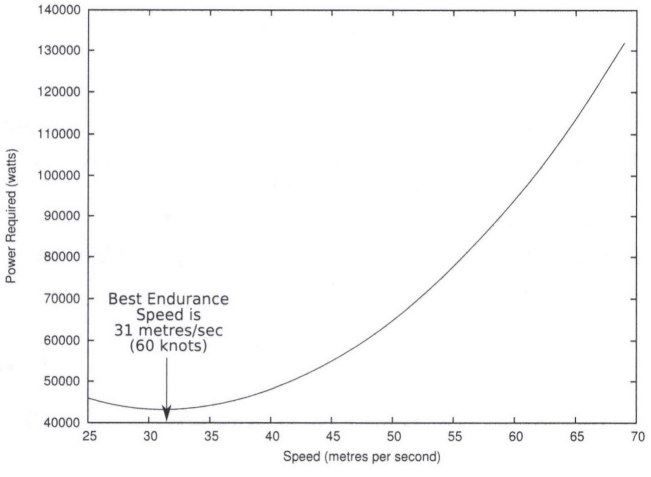

Figure 9.46: The Power Curve for a Cessna 172

The speed at which the required power is least is known as the *best endurance speed.* This is the speed at which the aircraft will stay aloft for the longest time on a tank of fuel. Flight at speeds slower than the best endurance speed is known as "slow flight".

It is instructive to superimpose a picture of propeller efficiency, and therefore the power it can provide, at different speeds (e.g., figure 9.45) onto the curve of power required: see figure 9.47.

The difference between the power that the propeller can provide and the power required to maintain straight and level flight at constant speed (represented by the vertical line in figure 9.47) represents the excess power available from the engine. The speed at which this excess power is at its maximum is the speed at which the aircraft can climb at its fastest rate: V_y.

9.6.5 Torque

Torque reaction is a direct application of Newton's Third Law of motion. As the engine applies a turning motion to the propeller, the propeller applies a turning

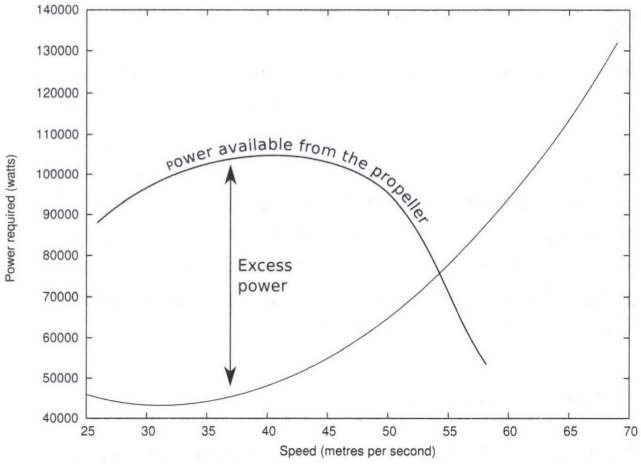

Figure 9.47: Visualising the Excess Power

motion to the aircraft in the opposite direction. You will have noticed this if you have ever wound up one of those small, balsa-wood toy aircraft with a propeller driven by a rubber band. It is easy to hold the propeller still and let the entire aircraft rotate. Even if the propeller is not held completely still, it still tends to impart a rolling motion to the aircraft.

During the takeoff run in an aircraft with an American engine (one that turns the propeller clockwise when viewed from the pilot's seat), the reaction on the aircraft tends to turn the aircraft anticlockwise—i.e., towards the left. The pilot has to apply right rudder to keep the aircraft moving in a straight line.

When the aircraft is in cruise, this turning force still acts, tending to make the aircraft roll to the left, but designers compensate for this by having the engine offset slightly.

9.6.6 Slipstream

The slipstream effect is another cause of yaw in a propeller-driven, single-engined aircraft. As the propeller turns, it pushes air backwards to create thrust, but the air is not driven directly backwards. The rotation of the propeller imparts a rotation to the air and it corkscrews its way back over the fuselage hitting, amongst other things, the side of the vertical tail. This sideways force is particularly large at high propeller speeds (when a lot of air is being moved backwards) and low forward speed (when the corkscrew is not being left behind). This means that it is mainly noticed during takeoff.

For a conventional North American engine that rotates clockwise when viewed from the cockpit, the slipstream winds around the fuselage and hits the vertical tail from the left-hand side, causing a yaw to the left.

9.6.7 Gyroscopic Effect

A rotating propeller acts as a gyroscope and when a force (actually a torque) is applied to a gyroscope to move it around one axis, it moves at right angles to the applied force. This means that, when an aircraft pitches nose up during its takeoff roll, the propeller (acting gyroscopically) will exert a sideways thrust on the nose of the aircraft. For most light aircraft this force is negligible although it can be felt in some tail-draggers when the tail-wheel is lifted.

9.6.8 Asymmetric Thrust

Asymmetric thrust (sometimes known as the P-Factor) is the effect that applies a turning moment to an aircraft around its vertical axis because the differences in the AoA between the upward- and downward-moving propeller blades. Since one blade has a higher angle of attack than the other, it produces more "lift" (thrust) and therefore causes the aircraft to yaw.

This phenomenon can actually only occur when the plane of the propeller is not perpendicular to the airflow: i.e., at high angles of attack. In tricycle wheel aircraft, even during the takeoff roll, the plane of the propeller is perpendicular to the airflow so asymmetric thrust does not occur. If the aircraft is flying nose-high to the airflow (i.e., at a high AoA) then the downward-going blade *does* have a higher AoA and produces more lift than the upward-going blade.

9.7 Load Factor

9.7.1 Load Factor During Banking

As described in section 9.5.10, when an aircraft is banking, part of its lift is being used to provide the force towards the centre of the circle to turn the aircraft. If the aircraft is to continue to fly at the same altitude then the wings need to provide greater lift than that required just to offset the aircraft's weight (see figure 9.48). Providing this additional lift puts greater stress on the wings, and we say that the *load factor* has increased. In straight and level flight, the load factor is 1.0 because the lift that the wings are required to generate is 1.0 × the weight of the aircraft. When the aircraft banks, this factor increases.

In figure 9.48 an aircraft is banking at an angle θ. The weight of the aircraft is still acting straight downward but the lift from the wings is no longer acting directly upward. The total lift can be thought of consisting of two parts: L_v acting vertically upward and L_h acting towards the centre of the turn. As explained in section 9.5.10, it is L_h that causes the aircraft to turn and is L_v that keeps the aircraft flying at a constant

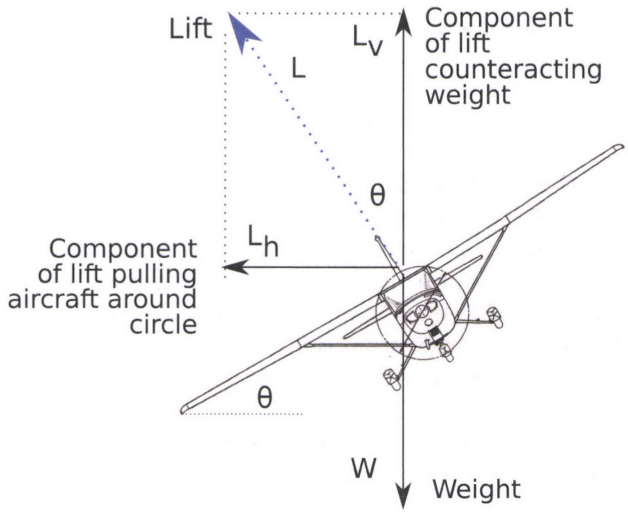

Figure 9.48: Load Factor in a Turn

altitude. Clearly, if the aircraft is to keep at a constant altitude, $L_v = W$. This means that the total lift (L) must be greater than the weight.

To find the magnitude of L we use a little trigonometry (not needed for the Transport Canada examination) and find that:

$$L = \frac{L_v}{\cos(\theta)} \tag{9.13}$$

$$W = L_v = L \times \cos(\theta) \tag{9.14}$$

This means that the total lift required to keep the aircraft at a constant altitude can be found by dividing the weight by the cosine of the angle of bank.

When there is no banking ($\theta = 0$), $\cos(0) = 1$, and the lift is equal to the weight as would be expected. The load factor is then said to be 1.0. As the angle of bank increases, so the load factor, the number of times the weight the lift has to provide, also increases. By the time a bank angle of 60° is reached, the lift required is

$$\frac{W}{\cos(60°)} = \frac{W}{0.5} = 2 \times W$$

At 60° of bank the lift required for level flight is twice the weight and the load factor is said to be 2.0.

Figure 9.49 sketches the load factor for angles of bank between 0° and 80°.

Exercise 78 *What is the load factor placed on an aircraft in a 40° banked turn?*

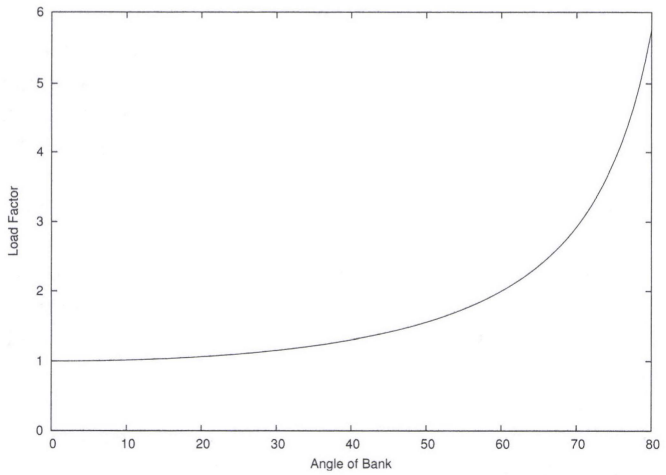

Figure 9.49: Load Factor for Different Bank Angles

9.7.2 Relationship of Load Factor to Stall Speed

As the load factor on an aircraft increases, so does its stall speed—it is easier to stall an aircraft when a high load factor is being applied to it. The relationship between the straight and level flight stall speed (S) and the stall speed when the load factor is n is given by the equation:

$$S_L = S \times \sqrt{n} \tag{9.15}$$

Exercise 79 *An aircraft that stalls at 50 knots in straight and level flight is in level flight, banking at an angle of* 40°. *What is its stall speed?*

9.7.3 Structural Limitations

It can be seen from equation 9.15 that when the load factor is 4, the stall speed doubles. Inversely, if an aircraft stalls at twice its normal stall speed, then the load factor is 4. The aircraft in figure 9.5 on page 169 is stalled at 200 knots. Assuming a straight-and-level stall speed of 70 knots, the load factor on the wings of that aircraft is over 8. This may well exceed the structural limitation of the aircraft.

The highest speed at which it is permissible to stall without potential damage to the aircraft is known as the manoeuvring speed (V_a).

9.7.4 Limit Load Factors

For aircraft certification purposes, the Federal Aviation Authority in the USA defines the concept of a *limit load factor*. This is the highest load factor that is expected in normal operations under different conditions (turbulence, gusting, etc.). Aircraft must be capable of handling load factors of up to 1.5 times the limit load factor without structural failure (although permanent twisting and bending of the airframe may result).

The standard limit load factors for different categories of flight are as follows:

- Normal Category: 3.8 to –1.52
- Utility Category (mild acrobatics, including spins): 4.4 to –1.76
- Acrobatic Category: 6.0 to –3.0

For aircraft with weights above 17,800 newtons (4,000 lbs-force), the limit load factors are smaller.

9.8 Stability

9.8.1 Aeroplane Axes

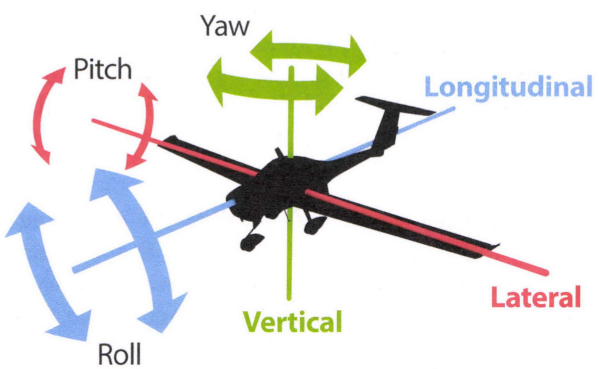

Figure 9.50: The Axes of an Aircraft

The three axes around which an aircraft can be considered to turn are illustrated in figure 9.50:

The Longitudinal Axis runs through the aircraft from its nose to tail. Rotation around this axis is known as *rolling*.

The Vertical Axis runs vertically through the aircraft. Rotation around this axis is called *yawing*. The vertical axis is sometimes called the *normal axis*.

The Lateral or Transverse Axis runs horizontally from wing-tip to wing-tip. Rotation around this axis is called *pitching*.

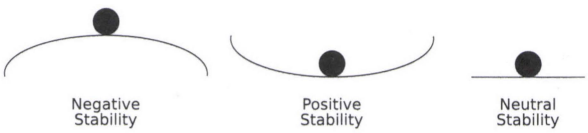

Figure 9.51: Types of Stability

9.8.2 Longitudinal, Lateral, Directional Stability

A system may possess one of three types of stability (see figure 9.51):

1. A system is said to be *Positively Stable* if it returns to its stable position after being displaced slightly. The ball in the centre of figure 9.51, if pushed to one side, will return (after a few oscillations) to its position in the bottom of the bowl—the ball is positively stable.
2. A system is said to be *Negatively Stable* if, once displaced, it tends to displace itself further. The ball on the left of figure 9.51 would, if pushed slightly, tend to move further from its point of stability—it is negatively stable.
3. A system is said to be *Neutrally Stable* if, when displaced slightly, it tends to stay in its new position. The ball on the right of figure 9.51 is on a rough, flat plane and, if nudged slightly, will neither roll back nor continue to roll away—it is neutrally stable.

The terms used for aircraft stability are confusing but actually quite logical: see figure 9.52. Stability around the lateral axis is known as *longitudinal* or pitch stability and stability around the longitudinal axis is called *lateral stability.*[16] Stability around the vertical axis is known as *directional stability.*

Stability about the ... axis	**Is known as ... Stability**	**Otherwise known as ...**
Longitudinal	Lateral	Roll Stability
Vertical	Directional	
Lateral or Transverse	Longitudinal	Pitch Stability

Figure 9.52: The Stability Axes

9.8.3 Inherent Stability

In principle an aircraft's stability can be described as being positive, negative or neutral in each of its three axes (see figure 9.50). An aircraft may, for example, have positive longitudinal stability. This means that, if a gust of wind pitches its nose up while it is in level flight then, perhaps after a few oscillations, it will return to its level attitude without any intervention by the pilot. An aircraft with negative longitudinal stability would behave differently: once the nose was lifted then, if no pilot action occurred, it would continue pitching upward.

An aircraft can be made inherently positively stable around all three axes but this may not be the design aim for some aircraft (e.g., for fighter aircraft that need to be nimble).

Normally, general aviation aircraft have positive longitudinal and directional stability and neutral or slightly negative lateral (roll) stability.

9.8.4 Achieving Stability

Longitudinal Stability

Positive longitudinal stability (i.e., nose pitching upward and downward around the lateral axis) can be achieved by ensuring that the centre of gravity is as far forward as possible. Then, if the aircraft is affected by a gust of wind that tends to move it upward, the nose will pitch down, reducing the lift of the wing and thus counteracting the gust. This is one reason why it is essential to ensure that the centre of gravity of an aircraft is within permitted limits before and during flight. If it is too far back, then continual control inputs may be needed to preserve longitudinal stability and it may become impossible to avoid larger and larger pilot-induced oscillations.

The horizontal tail (stabiliser) also contributes to the longitudinal stability of the aircraft. In normal flight this aerofoil produces "negative lift" to ensure that the aircraft remains balanced (see the upper part of figure 9.21 on page 176). If a gust of wind moves the nose of the aircraft downward, then the AoA on the horizontal tail increases and the negative lift increases, bringing the aircraft back to its stable position.

Directional Stability

Positive stability about the vertical axis (directional stability) is created through the design of the vertical tail: this is also an aerofoil and acts for directional stability much as the horizontal tail does for longitudinal stability. If a gust of wind from the right-hand side causes the nose of an aircraft to yaw anticlockwise (viewed from above) then the vertical tail acts as an aerofoil and generates "lift" to turn the tail clockwise, counteracting the yaw.

[16] If you look closely at figure 9.50 you will see that there is justification for these terms.

Lateral Stability

Most light aircraft have almost neutral lateral stability (i.e., rolling around the longitudinal axis)—if a bank is started by moving the ailerons and, once the bank angle is established, the control column is moved back to its central position, then the aircraft tends to keep the same bank angle until opposite aileron is applied. However, most light aircraft actually have a slight tendency towards a negative lateral stability—over a period of time the bank increases until a spiral dive is entered: see section 9.5.9. This tendency towards negative stability is, of course, particularly dangerous in IMC.

Positive lateral stability can be achieved in a number of ways:

1. By having a dihedral on the wings and by having swept-back wings. The effect of dihedral is awkward to explain with two-dimensional pictures but figure 9.53 attempts such an explanation. When the aircraft rolls because of a gust of wind under one wing, a component of the lift acts to one side and causes the aircraft to slip towards the side with the lower wing. This causes a relative airflow from the side that strikes the lower wing at a greater AoA: creating more lift on the lower wing and bringing the aircraft back to its stable position.

   When a wing drops, there is also interaction between the directional stability and the lateral stability—the wing dropping tends to cause a turn that is corrected by the vertical tail, again tending to raise the dropped wing.

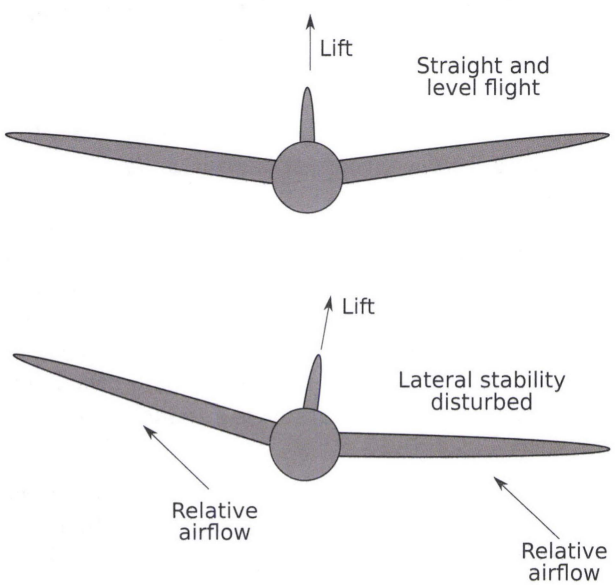

Figure 9.53: Effect of Dihedral

A wing with anhedral (i.e., drooping) causes the opposite effect: the aircraft becomes unstable around the longitudinal axis.

2. By having a high wing. Aircraft with high wings tend to be more laterally stable than those with low wings because, if one wing is deflected upward, the slip toward the low wing increases the AoA on the low wing as air is deflected by the fuselage. This only occurs if the aircraft slips—as for the dihedral effect discussed above.

3. By having swept-back wings. It can be shown that the slope of the Coefficient of Lift versus AoA curve (see figure 9.30 on page 180) for a swept wing is shallower than that for a straight wing: a wing perpendicular to the air flow creates more lift for a given angle of attack than one that is swept back. When a swept-wing aircraft is displaced around its longitudinal axis, it starts to slip as described above. The lower wing therefore passes through the relative airflow at an angle that is more perpendicular to the airflow than the higher wing. Consequently, more lift is created by the lower wing and the aircraft rights itself.

9.9 Flight Controls

9.9.1 Functions of Controls

Flight controls are required to move an aircraft around each of its three primary axes (see section 9.8.1):

1. The *longitudinal* axis. Movement around this axis is known as roll and is controlled by moving the aircraft's ailerons or, in the case of large aircraft, spoilers. When an aileron is moved downward on the wing it increases the lift on that wing and the wing rises, causing the aircraft to roll.

2. The *lateral* axis. Movement around this axis is known as pitch and is controlled by the elevator. The horizontal tail is an aerofoil and, as described in section 9.3.14, is normally fitted to provide "negative" lift—i.e., lift downward. The tail of the aircraft is pitched up or down by moving the elevator to change its AoA, thereby changing the lift it generates.

3. The *vertical* axis. Movement around this axis is known as yaw and is controlled by the rudder. The vertical tail is an aerofoil and it can be made to yaw to the left or right by moving the rudder. This changes its AoA, and thereby the "lift" it generates.

9.9.2 Yawing & Rolling

Roll and yaw are intimately linked. When an aircraft rolls, a portion of the lift of the wing acts sideways, causing the aircraft to yaw.

Similarly, if a pilot moves the rudder and thereby causes the aircraft to yaw, one wing moves faster than the other and therefore produces more lift. This causes a roll in the same direction as the yaw.

9.9.3 Adverse Yaw/Aileron Drag

When an aileron is moved downward on a wing it increases the lift on that wing. When the lift increases, so does the induced drag (see equation 9.7 on page 183). This additional induced drag on one wing causes the aircraft to yaw and the phenomenon is known as aileron drag. To counteract this yaw the pilot will typically apply rudder in the direction of the turn, but some aircraft have specific adaptations to reduce the need to use the rudder:

1. A *Frise Aileron* is an aileron constructed so that a portion of the upward-going aileron moves into the air-flow below the wing, causing parasitic drag. This is designed to match the drag created by the extra induced drag on the downward going aileron on the other wing.

2. A *Differential Aileron* is one where the down-going aileron moves through a smaller angle than the upward going one. The greater angle on the upward-going aileron causes more parasitic drag and this balances the extra induced drag on the other wing.

3. *Roll Spoilers.* On airliners the additional induced drag on the wing with the down-going aileron is matched by raising the spoiler on the other wing.

9.9.4 Static/Dynamic Control Balancing

When a control surface such as an aileron or elevator, is moved into an airflow, effort is required from the system applying the movement. In the case of a simple general aviation aircraft this may be the pilot acting directly on the surfaces by moving a control column connected to the surfaces by cables; in the case of more complex aircraft it may be the electrical or hydraulic system that moves the surfaces.

Whatever the source of the movement, it is advantageous to be able to balance some of the load and this is done in a number of ways including:

Control Horns. A control horn is just an extension of the control surface which projects ahead of the hinge. The air striking the horn assists the pilot to move the control surface. On a Cessna 172, for example, both the elevator and the rudder have such control horns: see figures 9.54 and 9.55.

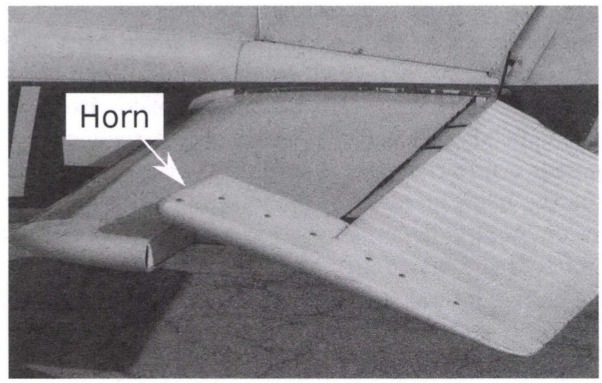

Figure 9.54: Elevator Control Horn on a Cessna 172

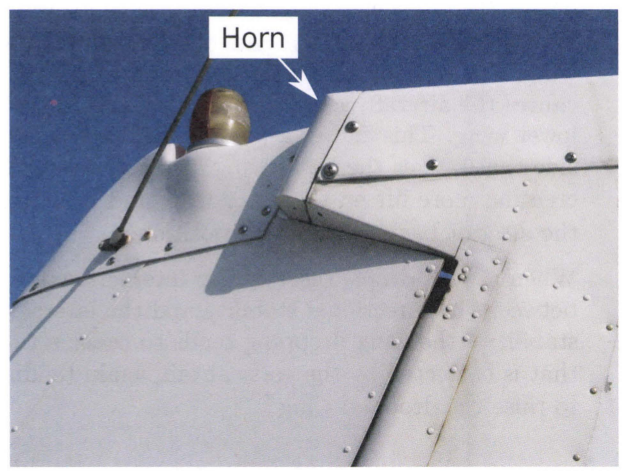

Figure 9.55: Rudder Control Horn on a Cessna 172

As control horns use the flow of the air itself to provide balance, they are known as *dynamic balances.*

Mass Balance. When a control surface is moved into the airflow, a low pressure area forms behind it. This tends to pull the surface back to its stable position. If the centre of gravity of the surface is behind the hinge, the surface tends to overshoot the stable point and the result is a tendency for the surface to flutter.

To solve this problem, the surface may be *balanced* to put its centre of gravity in line with the hinge. On a Cessna 172 the elevator and rudder balances are in the control horns while the aileron balances are strips of heavy metal fitted underneath the aileron.

Since mass balances are effectively fixed in the

design of the aircraft, they are known as *static balances.*

9.9.5 Trim/Trimming Devices

The horizontal and vertical tails are aerofoils controlling the pitch and yaw of the aircraft. As the aircraft flies, its weight changes and is redistributed (fuel is burned, passengers move, etc.) and to allow the pilot to fly "hands-off" it is necessary to be able to alter these aerofoils. This is achieved by moving *trim tabs* on the elevator and rudder.

In general, trim tabs on elevators are only useful for very light aircraft and on heavier aircraft the pitch of the entire horizontal tail is adjustable. This allows the trim to be adjusted without causing as much drag as a trim tab.

9.10 Answers to Exercises

This section provides some answers to the exercises given in this chapter.

Exercise 65

This wing has a 4% camber at 40% of the chord from the leading edge and the wing is 12% of the chord thick.

Exercise 66

This means that the camber line is identical with the chord line (i.e., $\delta = 0$ in figure 9.6). This only occurs if the wing is symmetrical.

Exercise 67

As the aircraft slows down, the AoA will need to be increased to preserve altitude. As the AoA increases, the centre of pressure moves forward. As the stall is approached, the centre of pressure reaches a point about 25% of the way from the leading edge of the wing and, as the stall occurs, the lift from the wing decreases rapidly and the centre of pressure moves towards the trailing edge.

Exercise 68

Had there been aircraft before Sir Isaac Newton, then people might have thought that in this situation, without the thrust being bigger than the drag, the aircraft would stop (and presumably fall out of the sky). Now, using Newton's First Law, we know that, as there is no net force acting (weight = lift, and thrust = drag), the aircraft will continue in a straight line at 100 knots.

Exercise 69

Using Newton's First Law, there is no net force acting horizontally (thrust = drag) so the aircraft will continue to fly at 100 knots. However there is a net force upward (because the lift is greater than the weight) so the aircraft will accelerate upward, its rate of climb increasing.

Exercise 70

If the thrust is less than the drag, then there is a net force retarding the aircraft and it will slow down. If the weight is greater than the lift then there is also a net force downward and it will descend. The aircraft is therefore slowing down and descending.

Exercise 71

It's true that, for a glider, drag must always be greater than thrust as long as it is flying at a constant altitude. A glider maintains flying speed once it is released from tow by putting its nose downward and turning some of its weight into thrust: see figure 9.56. The heavier the glider, the smaller the glide angle required to match the drag. For this reason, many competition gliders have their wings filled with water before a race. This water is jettisoned dramatically over the finish line before the glider, now much lighter, climbs and returns to land.

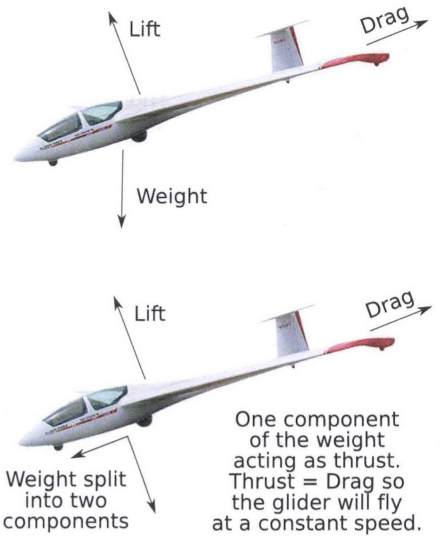

Figure 9.56: The Forces Acting on a Glider

As gliders are always descending in the air in which they're flying, glider pilots must minimise the drag of the glider and find air that is rising faster than the glider is descending. That this is possible is witnessed by glider height gains of well over

30,000 ft and glider flights over predeclared routes of more than 2,000 km.

Exercise 72

In order to apply equation 9.3 we must know the coefficient of lift when the AoA is 2.4° and the density of the air at 12,192 metres. Using figure 9.30, we can estimate the coefficient of lift as being about 0.52. As described in section 9.2.3, the standard air density at 12,192 metres is 0.30267 kg per cubic metre. We can now apply equation 9.3:

$$\begin{aligned} L &= \frac{C_L \times \rho \times v^2 \times A}{2} \\ &= \frac{0.52 \times 0.30267 \times 265.5 \times 265.5 \times 511}{2} \\ &= 2884606 \end{aligned}$$

The wing therefore provides 2,884,606 newtons (648,485 lbs-force) of lift.

Exercise 73

The aircraft will be in level cruise if the lift is equal to the weight (2,366,000 newtons). We therefore need to determine the coefficient of lift required to generate a lift of 2,366,000 newtons at 265.5 metres/second. Applying equation 9.3:

$$\begin{aligned} L &= \frac{C_L \times \rho \times v^2 \times A}{2} \\ 2366000 &= \frac{C_L \times 0.30267 \times 265.5^2 \times 511}{2} \\ 2366000 &= \frac{C_L \times 10902330}{2} \\ 2 \times 2366000 &= C_L \times 10902330 \\ 4732000 &= C_L \times 10902330 \end{aligned}$$

So $C_L = \frac{4732000}{10902330} \approx 0.434$. Using figure 9.30, we can see that an AoA of about 1.5° provides this coefficient of lift. The aircraft must therefore be trimmed to fly at an AoA of 1.5°.

Exercise 74

Using figure 9.33, it can be seen that the drag associated with a speed of 51.5 metres per second is about 947 newtons (about 213 lbs-force).

This could also be calculated using equation 9.4:

$$\begin{aligned} Dp &= C_{Dp} \times A \times \rho \times v^2 \\ &= 0.018 \times 16.2 \times 1.225 \times 51.5 \times 51.5 \\ &\approx 947 \end{aligned}$$

As the aircraft is not accelerating[17] the thrust must be equal to the drag and the thrust required is therefore 947 newtons (about 213 lbs-force).

[17] Scientifically, the term "accelerating" means that the speed or the direction is changing. Thus a body that is slowing down while travelling in a straight line or a body that is travelling in a circle at constant speed are both "accelerating".

Exercise 75

As the aircraft is in straight and level flight, the lift being created by the wings must be the same as its weight (10231 newtons). Applying equation 9.7:

$$\begin{aligned} D_i &= \frac{4 \times k \times L^2}{\pi \times r \times \rho \times v^2 \times A} \\ &= \frac{4 \times 1.1 \times 10231 \times 10231}{\pi \times 7.32 \times 1.225 \times 51.5 \times 51.5 \times 16.2} \\ &= \frac{460562788}{1210393} \\ &\approx 381 \end{aligned}$$

The induced drag is therefore approximately 381 newtons (85.5 lbs-force).

Exercise 76

Finding the radius of the turn is very simple. At "rate one" the aircraft will complete a circle in 2 minutes (120 seconds). An aircraft flying at 51.5 metres per second for 120 seconds will cover $51.5 \times 120 = 6180$ metres. A circle with a circumference of 6180 metres has a radius of $\frac{6180}{2 \times \pi} = 984$ metres (3,227 ft).

Finding the angle of bank requires some simple trigonometry. The force that needs to be applied to pull the aircraft around the turn can be found from equation 9.9:

$$\begin{aligned} F &= \frac{W \times v^2}{g \times R} \\ &= \frac{10231 \times 51.5 \times 51.5}{9.81 \times 984} \\ &= 2811 \end{aligned}$$

So a force of 2,811 newtons (about 632 lbs-force) needs to be applied to the aircraft. This is created by a component of the lift. The component of lift acting vertically upward has to remain at 10,231 newtons because the aircraft remains at the same altitude. Therefore, the vertical lift must be the same as the weight. These two values are illustrated in figure 9.43.

With those values available it is easy to calculate θ, the angle of bank:

$$\theta = \tan^{-1}\left(\frac{2811}{10231}\right) = 15.4$$

Therefore the aircraft has to bank at an angle of 15.4° to make a rate one turn.

Exercise 77

Firstly we need to convert some of the quantities into consistent units:

- 2500 rpm is $\frac{2500}{60} = 41.67$ revolutions per second
- 109 knots is 54.66 metres per second
- 75 inches is 1.9 metres

Then we can use equations 9.10 and 9.11 as follows:

1. Use equation 9.11 to calculate the advance ratio.

$$J = \frac{v}{n \times D} = \frac{54.66}{41.67 \times 1.9} = 0.690$$

2. Given a value of J we can use figure 9.45 to estimate the efficiency of the propeller: about 0.81 (i.e., the propeller is 81% efficient).
3. Given the efficiency, we can use equation 9.10 to estimate the thrust:

$$\begin{aligned} \eta &= \frac{T \times v}{P_{\text{avail}}} \\ 0.81 &= \frac{T \times 54.66}{112000} \\ T &= \frac{0.81 \times 112000}{54.66} \\ T &= 1660 \end{aligned}$$

So the thrust produced is 1,660 newtons (about 373 lbs-force).

Exercise 78

It is possible to estimate this by using figure 9.49 but easier just to use formula 9.13:

$$\begin{aligned} L &= \frac{L_v}{\cos(\theta)} \\ &= \frac{L_v}{\cos(40°)} \\ &\approx \frac{L_v}{0.766} \\ &= 1.305 \times L_v \end{aligned}$$

So the load factor is 1.305. For an aircraft such as a Cessna 172 at maximum gross weight of 2,300 lbs-force, the wings would have to generate $1.305 \times 2300 = 3003$ lbs-force to keep the aircraft in level flight.

Exercise 79

The load factor in the turn can be calculated by using equation 9.13:

$$n = \frac{1}{\cos(\theta)} = \frac{1}{\cos(40°)} \approx \frac{1}{0.766} = 1.305$$

Using a load factor of 1.305, the stall speed can be determined from equation 9.15:

$$S_L = S \times \sqrt{n} = 50 \times \sqrt{1.305} = 57.1$$

The stall speed is therefore just over 57 knots.

Chapter 10

Flight Instruments

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Flight instruments are changing rapidly, both in their operation and the manner in which they display their readings. Figure 10.1 illustrates two panels, and it is difficult to produce a book that does justice both to the traditional "steam gauges" in the lower part of that figure and the more modern primary flight displays in the upper part.

However, some things are common; the pitot-static system is an essential part of most aircraft, even if the pitot-static instruments are sometimes displayed on an electronic display and sometimes on a dedicated instrument. Similarly, mechanical gyroscopes are still to be found in most aircraft although they are rapidly being replaced by solid-state equivalents. This chapter covers these common, underlying technologies in detail and touches on some of the display techniques.

- Section 10.1 describes the pitot-static system and the associated instruments—the airspeed indicator, the vertical speed indicator and the altimeter.
- The magnetic compass is sufficiently complex to warrant a section to itself, section 10.2.
- Section 10.3 describes the principle of a gyroscope and shows how this is applied to the heading indicator, the turn-and-slip indicator, the turn co-ordinator and the attitude indicator.
- Section 10.4.2 describes Automatic Dependent Surveillance – Broadcast (ADS-B). Increasingly common and required in Canada, it is mandatory over much of the USA and the North Atlantic routes are taking advantage of it.
- Section 10.5 deals with a few other instruments used in the cockpit—the radar altimeter, the various devices for obtaining weather information in the air and collision avoidance equipment.

In general, the primary flight instruments measure one thing and display something else. A conventional altimeter, for example, measures atmospheric pressure, but, rather than displaying the pressure, it displays height above sea level. Figure 10.2 summarises what some of the flight instruments actually measure and what they display.

Figure 10.1: Aircraft Instrument Panels

10.1 Pitot-Static Instruments

Atmospheric pressure, the pressure with which the atmosphere presses down on an aircraft and its pilot, reduces with altitude. As described in section 4.2.2 on page 58, a *Standard Atmosphere* has been defined by the *International Organisation for Standardisation* (ISO) in document ISO 2533 to be one where the sea-level pressure is 101.325 kPa. This is equivalent to about 29.9212725″ of mercury.[1] This means that, on a standard day, the atmosphere at sea level is able to support a column of mercury 29.9212725″ high: see figure 3.1 on page 51. The International Civil Aviation Organisation (ICAO) has adopted the values from the ISO standard for use in aviation.

If the atmospheric pressure at a particular place is less than 29.92″ Hg,[2] the pressure is said to be *low*, and if it is greater than 29.92″ Hg it is said to be *high*.

The pitot-static instruments rely on changes in air pressure to operate.

[1] Pilots normally use 29.92″ because it's easier to remember.
[2] The chemical symbol for mercury is Hg.

10.1.1 The Pitot-Static System

The pitot-static system comprises two completely separate systems with no interconnection between them:

1. the *static* system that is connected to the airspeed indicator, vertical speed indicator and barometric altimeter.

2. the *pitot* system that is connected to the airspeed indicator.

Both the pitot and static systems are mechanisms to bring the outside atmospheric pressure to the appropriate instruments.

The Static System

The static system is simply a means of bringing the ambient atmospheric pressure outside the aircraft to the instruments requiring static pressure. Normally it is a tube connecting these instruments to one or more holes (static ports) in the side of the aircraft. It is important that static ports not be positioned where they are facing the airflow; otherwise their precise location is not important and varies between aircraft types. On a Cessna 172 the single static port is just ahead of the pilot door on the fuselage—see figure 10.4. On Piper Cherokees it is co-located with the pitot tube on the bottom of the wing although the two systems are still unconnected.

Alternate Static—Source/Errors

If a blockage occurs in the static port, then the pressure inside the static system will not change as the aircraft climbs and descends. This causes the pitot-static instruments to misread, sometimes with disastrous consequences. In 1996, maintenance workers forgot to remove tape that they had placed over the static ports on an Aeroperu Boeing 757 and the aircraft crashed, killing all 70 people on board. Unpressurised aircraft are equipped with *alternate static ports* that open inside the aircraft's cockpit. The air pressure in the cockpit is typically a little lower than the pressure outside and so the pitot-static instruments misread slightly, but this is better than not reading at all. This technique obviously doesn't work in pressurised aircraft where the cabin pressure is very different from the outside air pressure.

An alternative source of static pressure is essential for IFR flying and highly recommended for VFR. Given that the alternate static port is designed simply to get cabin pressure into the static system, as a last resort breaking the glass in one of the pitot-static instruments is sufficient. Although you could choose to sacrifice any pitot-static instrument, breaking its glass will damage it

Instrument	Measures	Displays
Airspeed Indicator	Difference in air pressure between pitot tube and static port	Airspeed
Vertical Speed Indicator	Rate at which air leaves or enters a container with a leak	Rate at which altitude is changing
Barometric Altimeter	Air pressure	Height above sea level
Radar Altimeter	Time for a radio signal to bounce off the ground	Height above ground
Magnetic Compass	Direction of the earth's magnetic field	Heading

Figure 10.2: The Flight Instruments

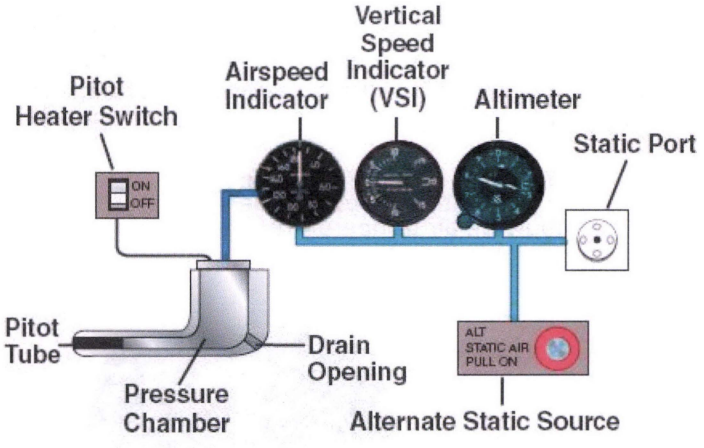

Figure 10.3: A Simple Pitot-Static System

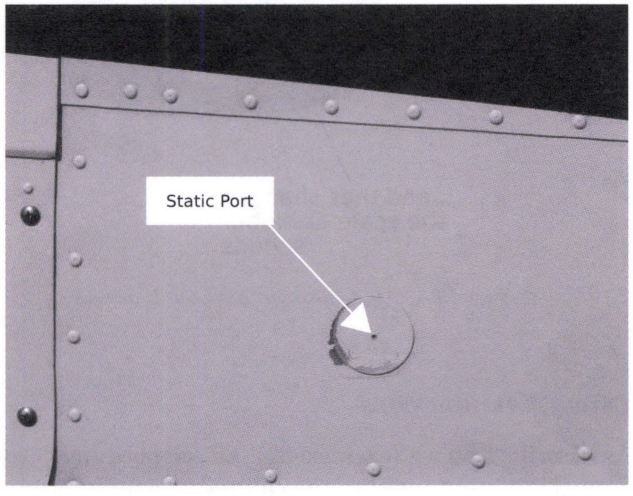

Figure 10.4: A Static Port on a Cessna 172

and so the vertical speed indicator is normally chosen as the one least needed for flight control.

The Pitot System

The pitot (pronounced "pete-oh") system is very similar to the static system except that the inlet, the pitot tube, is deliberately pointed into the airflow. In flight, the pressure in the pitot system is therefore higher than the pressure in the static system. Figure 10.5 illustrates a pitot tube on a Boeing 787.

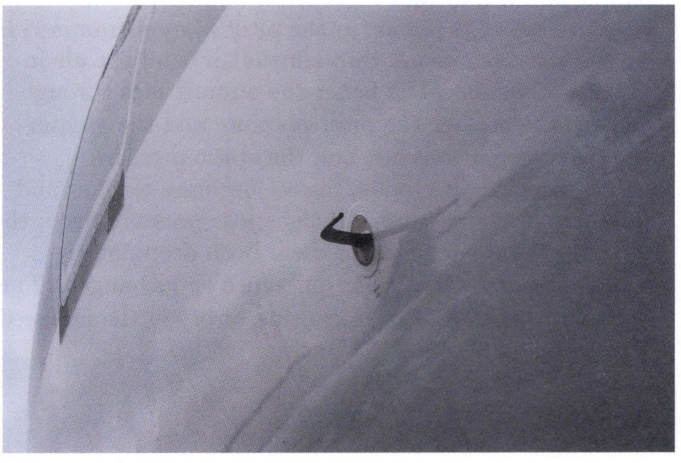

Figure 10.5: Pitot Tube of a Boeing 787 (Olivier Cleynen)

Blockage of the pitot tube can be as disastrous as blockage of the static port and much less easy to correct since there may be no *alternate pitot*. The most common blockages occur when insects nest in the pitot tube (hence the need for a cover over the tube—a cover that must be removed before flight!) or when ice forms in it during flight. To prevent icing when flying in cloud, pitot systems used for IFR or VFR-over-the-top flight must have heaters and these should be checked during the walk-around by turning the heater on and feeling the pitot tube. Be careful, because the pitot tube warms up very quickly and, once warm, is too hot to hold. Also, the heater expects to be kept cool in a moving air flow, so it should not be turned on for long when the aircraft is stationary.

10.1.2 Airspeed Indicator

Section 605.14 of the CARs states that

> No person shall conduct a take-off in a power-driven aircraft for the purpose of day VFR flight unless it is equipped with ... an airspeed indicator.

If the aircraft is to be used for VFR over-the-top or IFR flying, then the airspeed indicator must have "a means of preventing malfunction caused by icing for each airspeed indicating system."[3]

Principle of Operation

The airspeed indicator measures the difference in pressure between the air in the pitot system (rammed in by the aircraft moving through the air) and the air in the static system. The faster the aircraft flies through the air, the greater the pitot pressure and the greater the difference between it and the static pressure.

As the aircraft climbs, the air becomes thinner and both the pitot pressure and the static pressure drop; the airspeed indicator relies on them both dropping the same amount so that their difference is unchanged. This does not actually happen, causing errors in the airspeed readings—see *Errors/Malfunction* below.

Definitions—IAS/CAS/TAS

IAS, Indicated Airspeed, is the speed read from the airspeed indicator.

CAS, Calibrated Airspeed, is the indicated airspeed corrected for errors introduced by the positioning of the pitot tube and static port. The difference between IAS and CAS is normally only 1 or 2 knots and can be found in a table in the pilot operating handbook for the aircraft.

TAS, True Airspeed, is the actual speed at which the aircraft is moving through the air. Because of various errors in the airspeed indicator (see below), the true airspeed is normally higher than that indicated. The conversion of a CAS into a TAS requires knowledge of the pressure altitude and outside air temperature. Armed with these values, an aviation calculator can be used to find the TAS.

As a simple rule of thumb, the true airspeed of an aircraft can be approximated by reading the airspeed indicator (correcting the IAS to CAS if you're fussy) and adding about 2% of the indicated airspeed per thousand feet of (pressure) altitude. This is not strictly accurate because it ignores temperature, but it is often adequate for normal use.

[3]This is normally satisfied by having a heater in the pitot tube.

Exercise 80 *You are flying a Cessna 172 at 8,000 ft ASL and the airspeed indicator reads 95 knots. Using the rule of thumb, what is your TAS?*

Possible answers to the exercises are given at the end of the chapter, starting on page 226.

To avoid the pilot having to make this type of calculation, many airspeed indicators are fitted with a sliding scale that changes the speed markings when the (pressure) altitude is aligned with the outside air temperature—see figure 10.6. The computer behind a more sophisticated airspeed indicator, such as that shown in figure 10.7, will automatically carry out the necessary conversion and display a corrected value.

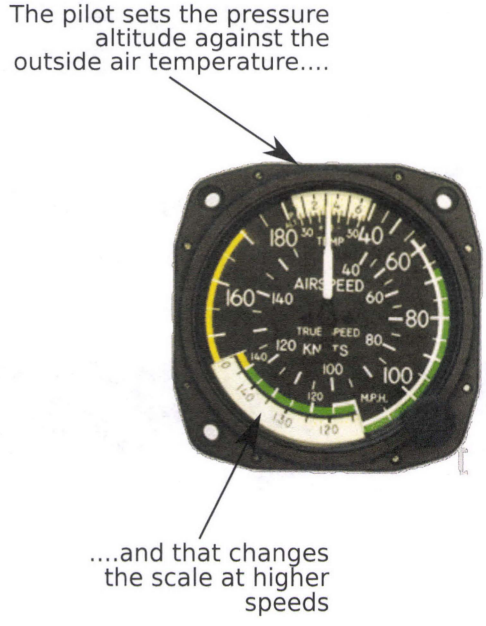

Figure 10.6: An Adjustable Airspeed Indicator

Errors/Malfunctions

As described above (exercise 80), an airspeed indicator normally displays neither the calibrated nor the true airspeed of the aircraft. This is not actually an error or malfunction; it is a characteristic of the measuring system for which the pilot can make allowances and it is not as important as might be thought because many aircraft characteristics (e.g., stall speed) also change with altitude and are associated with indicated rather than true airspeed.

However, there *are* errors associated with the airspeed indicator misreading if the pitot or static port becomes blocked (see exercises 81 and 82 on page 208).

Another source of error occurs if the pitot tube is not facing directly into the air-stream or the static port *is* facing partially into it. This occurs when the aircraft is slipping—while slipping, the airspeed readings cannot be trusted.

Markings

Humans, particularly when under pressure, find it much easier to read an analogue rather than digital display. You may have found this with wristwatches: a quick glance at an analogue watch and you know that it's almost a quarter to twelve without even having to verbalise what you see. With a digital watch, however, a display of 11:43 has to be consciously translated.

Figure 10.7 illustrates an airspeed display strip (or "tape") from a primary flight display (PFD). This combines an analogue strip (ranging in the picture from 140 to 200 knots) with a digital readout of the true airspeed (170 knots), the correction between calibrated and true airspeed having been carried out by the computer driving the display. On a more sophisticated PFD there would be a number above and an arrow to the right of the strip indicating the "commanded" airspeed—the airspeed at which the autopilot has been programmed to fly.

This type of airspeed indication is now ubiquitous in PFDs although it has been criticised by human factors experts. Studies have shown that, while a PFD readout of airspeed (figure 10.7) is read more accurately than a "clock-style" ASI (0.3% of readings being in error rather than 0.7%), it takes longer to read: an average of 2.3 rather than 1.7 seconds. Its primary problem is that it does not conform to the *principle of the moving part*. This says that, to reduce human error, the indications on a gauge should be configured in the same direction as the action required to change them. In this case, to increase speed, the natural action would be to push the stick forward and lower the aircraft's nose. Unfortunately, the higher speeds are at the top, rather than the bottom, of the strip, something that a pilot under pressure could associate with pulling the nose up.

Even when equipped with a PFD, an aircraft is also required to have a non-electrical ASI of the type shown in figure 10.6. This type of ASI has various speeds marked by colour bands:

- A white arc within which full flaps can be deployed. In general, partial flaps can be deployed above this range. The lower end of the white arc indicates the speed at which the aircraft will stall in level flight with the flaps extended.

- A green arc indicating the normal flying speeds. The lower end of this arc indicates the speed at which the aircraft will stall in level flight with the flaps retracted.

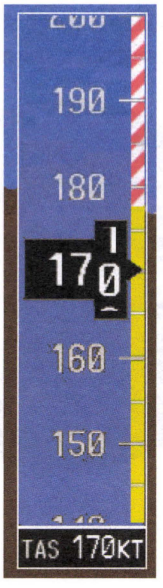

Figure 10.7: A PFD Airspeed Indicator Display

- On twin-engined aircraft:
  - a red line within the green arc indicating the minimum indicated airspeed at which the aircraft can be controlled with the critical engine[4] inoperative.
  - a blue line indicating the best rate of climb with the aircraft's critical engine inoperative.

- A yellow arc indicating speeds at which sudden and large control deflections might damage the airframe.

- A red line at the top of the yellow arc indicating the maximum speed at which the aircraft may be flown. Speeds above this may result in structural damage.

The Lift Reserve Indicator

One problem with the conventional pitot-static airspeed indicator is that it works least well when it is most needed—when the aircraft is flying slowly and possibly approaching a stall.

The *Lift Reserve Indicator* (LRI), when used with an airspeed indicator, can resolve this problem. It effectively displays the aircraft's angle of attack (see section 9.2.6 on page 169) and airspeed on one display and is accurate and sensitive even when the aircraft is flying slowly. It automatically takes into account the

[4]The critical engine of a multi-engine aircraft is the one whose failure would result in the most adverse effects on the aircraft's handling and performance.

different stall speeds depending on the actual weight of the aircraft (and the corresponding wing loading).

Figure 10.8: A LRI Display

The LRI operates by measuring the differential pressure across a probe below the wing and the aircraft's angle of attack. The display has three coloured arcs (see figure 10.8):

1. an arc indicating a flight configuration with sufficient lift
2. an arc showing a transition phase where lift is being generated but the angle of attack is high
3. an arc indicating that the angle of attack is preventing lift from being generated

The LRI is particularly useful for determining approach speeds into short fields and the minimum speed required for lift-off when departing a short field.

10.1.3 Vertical Speed Indicator

The vertical speed indicator is also known as the *variometer*, particularly in soaring (gliding) circles. It indicates whether the aircraft is climbing or descending and, in North America, the scale is marked in feet per minute or knots (100 feet per minute is almost exactly a knot).

The vertical speed indicator is a crucial instrument for a glider pilot and so that she doesn't have to look inside the aircraft to determine whether the glider is climbing or descending, it is often connected to a loud-speaker and tone generator. In a gentle climb the loud-speaker clicks infrequently. As the rate of climb increases, the clicks become more frequent until they become a tone. The tone rises in pitch as the lift increases further.

Principle of Operation

The vertical speed indicator is connected only to the static system but operates by measuring a differential

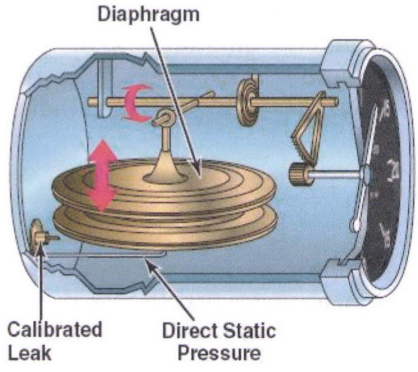

Figure 10.9: Principle of the Vertical Speed Indicator

pressure. It contains a slightly flexible diaphragm in a rigid airtight case. The inside of the diaphragm is connected directly to the static line of the pitot-static system. The case is also connected to the static system, but through a calibrated leak—see figure 10.9 that illustrates this diagrammatically.

Both the diaphragm and the case receive air from the static system and, when the aircraft is flying at a constant altitude, the air pressures are the same inside and outside the diaphragm and the indicator reads zero.

As the aircraft descends, the pressure in the static system increases and the pressure inside the diaphragm immediately responds. Because the calibrated leak is small, the pressure outside the diaphragm changes more slowly and the diaphragm expands slightly, causing the indicator to record a loss of altitude.

The vertical speed indicator displays two different types of information:

1. Trend information—an immediate indication of an increase or decrease in the rate of climb or descent.
2. Rate information—a stabilised rate of change in altitude.

For example, if you are maintaining a steady 500 ft per minute climb and you lower the nose slightly, the vertical speed indicator immediately senses this change and indicates a decrease in the rate of climb—trend information. After a short time, known as the lag time, the vertical speed indicator stabilises on the new rate of climb, say 450 ft per minute—rate information.

Errors/Malfunctions

A glider pilot really needs to know how much altitude is being gained or lost by the aircraft entering rising or falling air. Altitude lost when the pilot pushes the nose down is less important because the aircraft speeds up and much of the original height can be regained by converting that extra speed back into height by pulling

the nose up again. A conventional vertical speed indicator cannot differentiate between height gained or lost by virtue of rising or falling air and height gained or lost because of energy conversion. Most gliders are therefore equipped with *total energy* compensated variometers. These perform the necessary computations to remove changes in height caused by changes in speed.

Lag

The time from the initial change in the rate of climb until the vertical speed indicator displays an accurate indication of the new rate is called the lag. Typically this can be 5 to 10 seconds. Some aircraft are fitted with instantaneous vertical speed indicators (IVSIs) that incorporate accelerometers to compensate for lag.

10.1.4 Barometric Altimeter

Section 605.14 of the CARs states that

> No person shall conduct a take-off in a power-driven aircraft for the purpose of day VFR flight unless it is equipped ... where the aircraft is operated in controlled airspace, [with] a sensitive altimeter adjustable for barometric pressure.

Principle of Operation

As indicated in figure 10.2, the barometric altimeter is nothing more than a barometer measuring the pressure of the air in the static system. The higher the aircraft, the lower the static pressure, therefore measuring pressure will give an approximation of the altitude. This is displayed on a digital display or an analogue rotary dial (see figure 10.10). As the atmospheric pressure differs from day-to-day and from place-to-place, the pilot needs to know the local atmospheric pressure and adjust the altimeter accordingly.

Errors/Malfunctions

Most errors associated with the barometric altimeter occur for the following reasons:

1. The sea-level pressure for the area is not known or has been incorrectly set by the pilot.

2. The altimeter measures atmospheric pressure and relies on the fact that this decreases with height. Unfortunately the manner in which it decreases is very complex. By 18,000 ft it has dropped by about 50% of its value at sea level and it drops roughly by a further 50% for each additional 18,000 ft height gain. Figure 10.11 illustrates the manner in which the pressure drops with altitude in a perfectly dry

Figure 10.10: Altimeter Indicator Displays

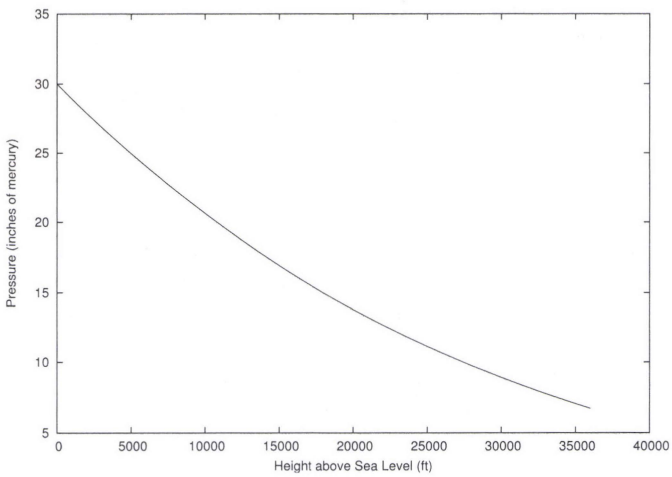

Figure 10.11: Variation of Pressure with Altitude

atmosphere where the temperature drops by exactly 1.9812 Cdeg per 1,000 ft. Even there, you will see that the change in pressure is not linear although for low altitudes where general aviation aircraft typically fly (up to about 10,000 ft ASL) it *is* reasonably linear.

This gives rise to error because the real atmosphere through which the aircraft is flying:

(a) is never completely dry.

(b) is rarely at standard temperature and does not cool at exactly 1.9812 Cdeg per 1,000 ft. This is a major cause of altimeter error: if the temperature is above normal then the altimeter will under-read and in cold weather will over-read. The explanation of this can be found in section 4.5.4 on page 63. NAV CANADA publishes a table in the general

pages of the *Canada Air Pilot* giving correction values to be added to various altitudes during IFR approaches in cold weather. For example, at 2,000 ft above the station measuring the pressure, if the temperature is −30°C, 380 ft must be added to all heights on approach plates.

In addition to these errors in the display, there is also the human factors issue of pilots misreading altimeters.

Anecdote 28 *One day when I was instructing it so happened that, since the training aircraft had last been used, the atmospheric pressure had dropped in such a way as to cause the altimeters to over-read by almost exactly 1,000 ft. As we were working out of an airport without an altimeter setting, the students set the altitude of the airport rather than the sea level pressure on the altimeters before takeoff. The first student of the day didn't notice the 1,000 ft error until well into the flight. Seeing this as a training opportunity, I reset the altimeter to its incorrect value for every other student that day. Almost no one noticed the 1,000 ft error!*

Above 18,000 ft and in the north of Canada (where there are few stations measuring and broadcasting pressure) the altimeter is set to 29.92″ Hg and aircraft fly at *flight levels* rather than at a precise altitude. An aircraft is flying at FL230, for example, if the altimeter reads 23,000 ft when set to 29.92″ Hg. If the local pressure is not standard then the aircraft will not be flying at 23,000 ft ASL, but all other aircraft flying at FL230 will be flying at the same altitude.

Exam Hint 20 *Most examinations contain at least one question about the behaviour of the pitot-static instruments if the static port or pitot tube blocks. It is unclear why there is this obsession with blocked pitot-static systems. My recommendation is not to try to learn the answers—they are easy enough to work out as demonstrated by the examples that follow.*

Exercise 81 *You are in a steady climb at a constant speed when the static port ices over. How will this affect the pitot-static instruments?*

Exercise 82 *You are in a steady descent at a constant speed when the pitot tube blocks. How will this affect the pitot-static instruments?*

Anecdote 29 *Pitot tube blockage is not just a theoretical problem to be learned for written examinations. I was taking off one day from Iroquois aerodrome in Ontario. The runway at Iroquois is relatively short (2,000 ft) and its paved section is very narrow (23 ft). Normally I check the operation of the airspeed indicator as I start the ground roll and, if anything is wrong, pull the throttle to idle and stop ahead on the runway. In this case, I was concentrating on holding the aircraft on the narrow runway and didn't look at the airspeed indicator until I felt we were approaching rotation speed. The airspeed was apparently 20 knots. This was clearly wrong but, as I had insufficient runway ahead of me to stop, I took off. The airspeed indicator rose to about 50 knots in cruise flight and held that value until I was on the ground again. Due to thunderstorms, I diverted into Ottawa International and even using its very long and very wide runway, landing without an airspeed indicator was difficult—resulting in a bounce, even in an aircraft I knew well. I used the GPS ground speed on approach, making an adjustment for the wind, but reading a digital display is harder than glancing at an analogue instrument. It is interesting to speculate what would have happened had I been departing IFR into a 500 ft overcast. The problem was that insects had blocked the pitot tube in the couple of hours we had spent on the ground in Iroquois—I have learned to put the pitot cover on even if I'm only leaving the aircraft for a few minutes.*

10.1.5 Encoding Altimeter

Principle of Operation

The terms *encoding altimeter* and *blind encoder* refer to different devices but encoding altimeters have now more or less disappeared from general aviation aircraft, to be replaced by blind encoders.

An encoding altimeter is a standard barometric altimeter that, in addition to displaying the air pressure in the static system, encodes the altitude corresponding to 29.92″ Hg digitally and makes it available to the aircraft's transponder and GPS.[5] Note that moving the pressure setting on an encoding altimeter moves the

[5]GPS units can provide altitude information from the GPS signals but this is typically inaccurate: basically the datum over which the measurement is made is simple, whereas the shape of the earth is complex and the arrangements of satellites that give good lateral position (satellites well spread out about the same distance above the horizon) are precisely the arrangements that give poor vertical measurements. By providing barometric altitude to the GPS, vertical guidance can be given during some instrument approaches.

displayed altitude but makes no change to the encoded altitude.

A blind encoder is basically a standard barometric altimeter without a display and without a means of setting the sea-level pressure (always assumed to be 29.92″ Hg—the system therefore measuring pressure altitude). It is normally a simple electronic board (see figure 10.12) with outputs to connect it to the aircraft's transponder and GPS.

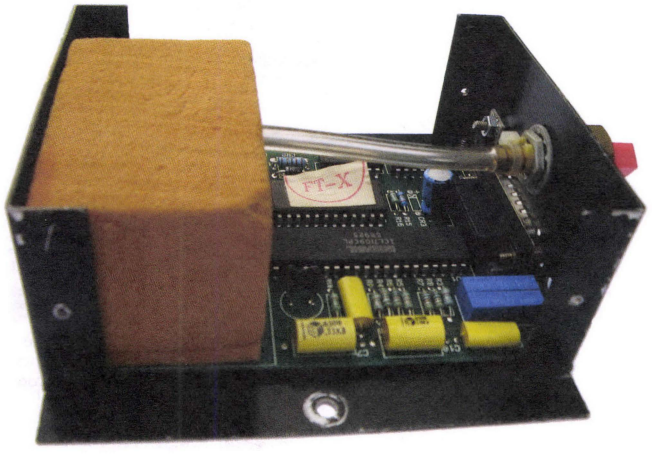

Figure 10.12: A Blind Encoder

The actual code transmitted by the transponder as a result of a mode C interrogation is the altitude provided by the encoding altimeter or blind encoder rounded to the nearest 100 ft as a series of twelve bits (0s and 1s) using what is known as a *Gray Encoding*. The height of 0 ft (sea level), for example, is transmitted as 000011010000 and 100 ft as 000011110000. Note that only one bit has changed between these two adjacent values—this is a characteristic of Gray encoding.

Errors/Malfunctions

In addition to the errors inherent in any barometric altimeter (see page 207), the encoding altimeter or blind encoder is also subject to bits (0s and 1s) sticking in the altitude encoding (i.e., not changing as required).

Anecdote 30 *I was once in an aircraft in which the 4th bit from the left stuck at 1. This was not a problem until the aircraft climbed from 4,700 ft (001110001000) to 4,800 ft. This should have been encoded as 001010001000 but, because of the stuck bit, was transmitted as 001110001000 by the transponder. This corresponds to 4,600 ft. As the aircraft continued to climb, the transponder sent lower and lower altitudes until we levelled off at 6,500 ft at which time the transponder was sending 001100010000 which corresponds to 3,200 ft. We were in a mountainous area over Vermont, USA, and the controller kept warning us that we were too low. It was only after we landed that I realised why he had been concerned.*

10.2 The Magnetic Compass

Section 605.14 of the CARs states that

> No person shall conduct a take-off in a power-driven aircraft for the purpose of day VFR flight unless it is equipped with . . . a magnetic compass or a magnetic direction indicator that operates independently of the aircraft electrical generating system.

The magnetic compass was invented by the Chinese around 200 BC, primarily as a way to tell fortunes. It is not clear precisely when it started to be used for navigation but a portable magnetic compass was certainly in common use in the 9th century CE, again by the Chinese. With the advent of GPS its use is rapidly declining, and more pilots fly tracks indicated by GPS rather than headings displayed on a magnetic compass.

10.2.1 Principle of Operation

The earth acts like a large bar magnet with one pole close to the earth's North Pole (at the *North Magnetic Pole*) and the other close to its South Pole (at the *South Magnetic Pole*). A suspended magnet will point to one or other of these poles.

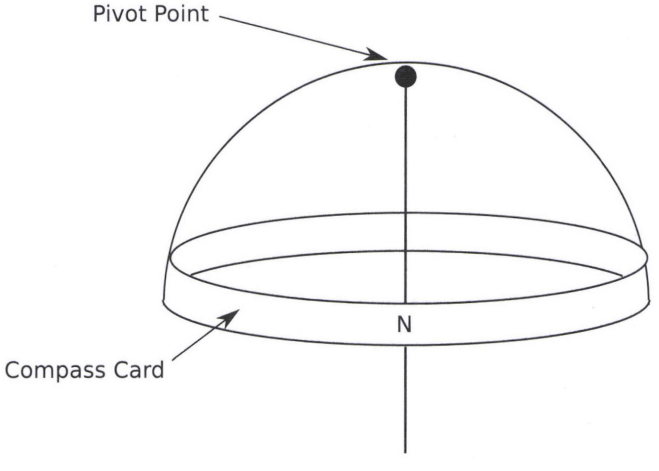

Figure 10.13: The Compass Pivot Point

The traditional, wet magnetic compass[6] in an aircraft

[6] A conventional aircraft compass is known as a "wet" or even "whiskey" compass because it contains liquid in which the magnetic pointer floats.

is simply a suspended magnet, typically shaped like an upside-down bowl suspended from underneath at a point higher than its centre of gravity (see figure 10.13).

10.2.2 Variation

Compass use would be much simpler if the North Magnetic Pole were at the earth's North Pole and the South Magnetic Pole at its South Pole. Unfortunately, because of movements within the earth's core, they are not. In the last 2,000 years, the north magnetic pole has moved thousands of kilometres over the Arctic and about 300 years ago it was located in Greenland. In 2007 it lay near Ellef Ringnes Island in Nunavut at about 83.95° North 120.72° West: see figure 10.14.

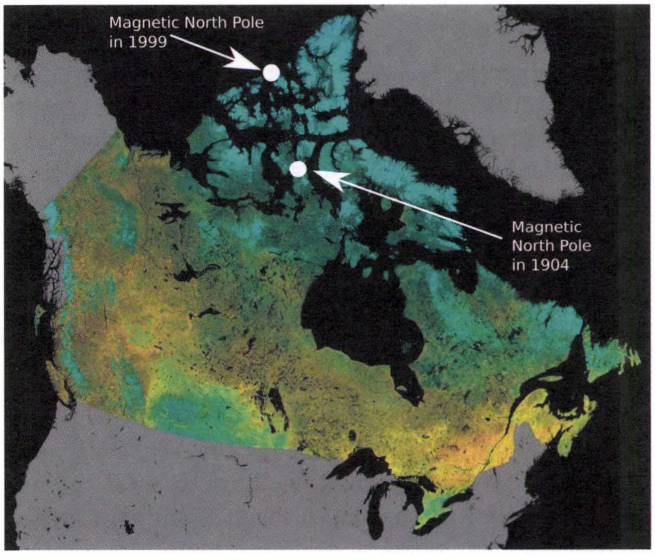

Figure 10.14: The Magnetic North Pole (NOAA)

Several times in the earth's history the north and south magnetic poles have switched, and some geologists believe that another switch will happen in the next few thousand years. Before a switch has occurred in the past, the strength of the magnetic field has decreased and, in the last 100 years, its strength has depleted by 5% — evidence that such a switch may be in progress. Measurements made in 2014 indicate that the decline may have speeded up to 5% per decade (rather than per century) and the switch may occur well within the next 2,000 years.

From any point on the earth a great circle line can be drawn to the North Magnetic Pole and another line to the earth's North Pole. The angle between these two lines is known as the *variation* or *declination* at that point.[7]

[7]Sailors and pilots tend to use the term *variation* while earth-bound navigators use *declination*. This may be because celestial navigation uses the term *declination* for a different concept.

In Halifax, on Canada's east coast, the compass points 19° west of true north (i.e, the direction to the real North Pole). Moving westwards, by the time you reach Ottawa, the compass is pointing 14° too far west. Somewhere between Thunder Bay and Fort Frances, Ontario, the compass points due north because the magnetic north pole and the earth's north pole align. By Fort Frances the compass is pointing 1° too far east. By Vancouver it points 19° too far east. See figure 10.15.

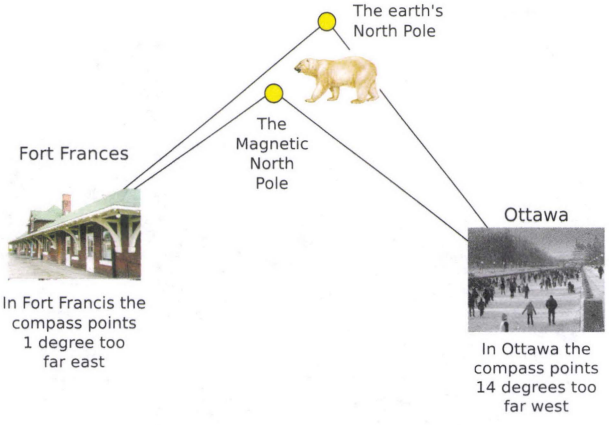

Figure 10.15: Magnetic Variation across Canada

The Chinese first measured magnetic variation in about 720 AD. In Europe, the first precise measurement was not made until 1510 when Georg Hartman measured the variation in Rome. In 1700, Edmund Halley produced the first variation chart of the Atlantic Ocean, using "contour lines" to join places with the same variation—now known as isogonals.

Exercise 83 *An aircraft lands at night at an airport where the magnetic variation is 20° W. The pilot, a keen amateur astronomer, notices during the roll out along the runway that the aircraft is aiming directly at Polaris, the pole star. What is the number of the runway on which she landed?*

Exam Hint 21 *The type of problem illustrated in example 83 is very easy to get wrong unless you draw a picture. In multiple-choice form, the given answers would probably be 36, 20, 02 and 34.*

10.2.3 Magnetic Dip

The earth's lines of magnetic field are only parallel with the surface of the earth at the equator (see figure 10.16)

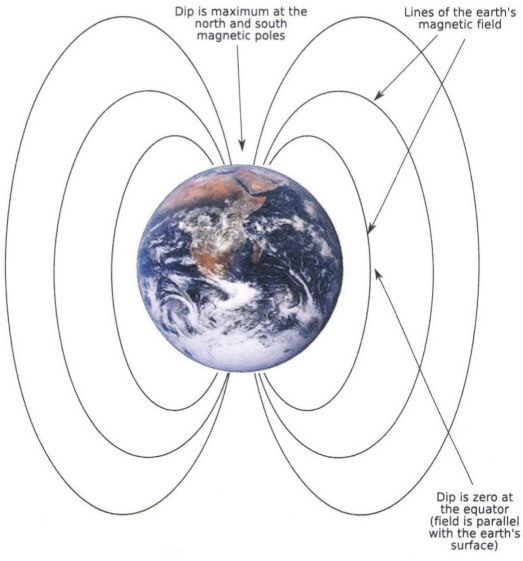

Figure 10.16: Magnetic Dip

and, at the magnetic north or south pole they are vertical. This means that a compass needle, if freely suspended, would appear as shown in figure 10.17—it would *dip*. The dip is vertical at the north and south magnetic poles and a compass that is allowed to swing only in the horizontal plane (e.g., a hiker's compass) will point in random directions at these positions.

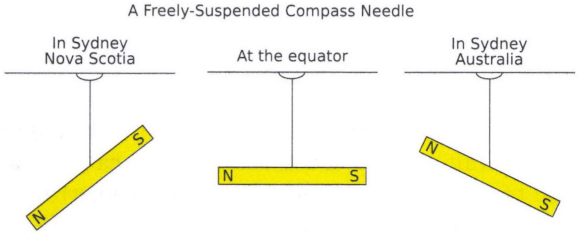

Figure 10.17: The Effects of Dip (not to scale)

A moving compass is susceptible to errors caused by dip at all points except at the equator, and these errors become more pronounced the further from the equator the compass is being used. When the aircraft is flying straight and level at a constant speed, the weight of the rim of the compass bowl effectively overrides the effect of dip. When the aircraft accelerates or banks, however, the dip causes the compass to read erroneously.

Figure 10.18 lists the dip angles for some airports in Canada. It can be seen that the further north the airport lies, the greater the dip angle. As the earth's magnetic field changes, the dip angle also changes. In early 2024, the dip angle at Inuvik (CYEV) was changing by 3.3 minutes of angle per year.

Airport	Latitude	Dip
Pelee Island (CYPT)	41°46′42″ N	60.09°
Ottawa, Rockcliffe (CYRO)	45°27′37″ N	69.75°
Kuujjuarapik (CYGW)	55°16′55″ N	76.85°
Churchill (CYYQ)	58°44′21″ N	80.04°
Inuvik (CYEV)	68°18′15″ N	81.12°

Figure 10.18: Dip Angles at Selected Airports

10.2.4 Reading the Compass

The traditional magnetic compass in many light aircraft is an extremely confusing instrument to read because it gives its information backwards relative to the heading indicator—see figure 1.10 on page 22.

Because of this, some pilots fit vertical card magnetic compasses into their aircraft—see figure 10.19. These suffer from the same errors as any magnetic compass but at least their displays align with the heading indicator.

Figure 10.19: A Vertical Card Magnetic Compass

10.2.5 Errors

The main errors when a compass is used away from the poles are as follows (see figure 10.20):

- **Northerly Turning Error.** This error depends on the heading, the direction of the turn, the angle of bank, the hemisphere in which the aircraft is flying and the dip angle at the location. In the northern hemisphere, the error causes the compass to lead (i.e., be ahead of) the aircraft on southerly headings and to lag (i.e., be behind) on northerly headings. In steep turns, where the sum of the dip angle and bank angle is greater than 90°, the compass will "hang up" and not respond as the aircraft turns through a complete circle.

Although it is not needed for the Transport Canada examination, it is interesting to calculate the effect of the northerly turning error on a compass. This is given by:

$$H_c = \tan^{-1}\left(\frac{|\sin(H_m)\cos(\theta) - \tan(\mu)\sin(\theta)|}{\cos(H_m)}\right) \tag{10.1}$$

where H_c is the compass heading, H_m is the actual magnetic heading of the aircraft, θ is its bank angle and μ is the dip angle (down being positive).

- **Acceleration Error.** This error is also caused by dip. In the northern hemisphere, if an aircraft accelerates on other than a due northerly or due southerly heading, then the compass swings to the north, even if the aircraft's heading is unchanged. If the aircraft decelerates, the compass swings to the south.

  Although it is not needed for the Transport Canada examination, the compass' heading during acceleration can be calculated:

$$H_c = \tan^{-1}\left(\frac{\sin(H_m)}{\alpha + \beta}\right) \tag{10.2}$$

with:

$$\alpha = \cos(H_m)\cos(\tan^{-1}(a)) \tag{10.3}$$

$$\beta = \tan(\mu)\sin(\tan^{-1}(a)) \tag{10.4}$$

where H_c is the compass heading, H_m is the actual magnetic heading, a is the aircraft's acceleration (as a multiple of $g = 9.80665\ \text{ms}^{-2}$) and μ is the dip angle. Because of the presence of $\sin(H_m)$ in the numerator of this equation, it is clear that no acceleration error will occur if the aircraft is flying directly magnetic north or directly magnetic south.

Exam Hint 22 *The mnemonic ANDS (Acceleration → Northerly, Deceleration → Southerly) can be used to remember the direction of acceleration errors.*

Exercise 84 *You are flying over Ottawa's airport and make a 20° banked turn. As you pass through a magnetic heading of 045°, what does your compass read?*

Exercise 85 *You are flying directly overhead of the Ottawa airport on a heading of 045° and pull the carburetor heat control. This has the effect of decelerating the aircraft by 0.1g. What does the compass read during the deceleration?*

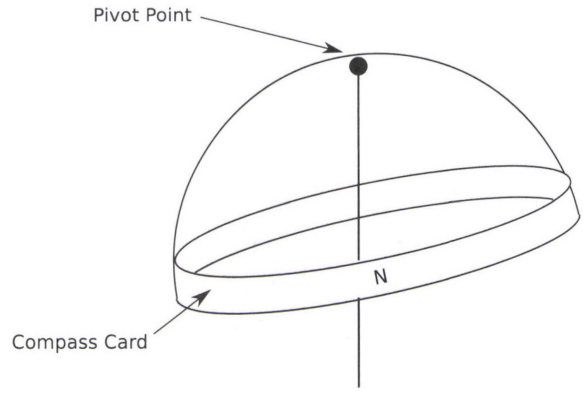

Figure 10.20: The Compass as Affected by Magnetic Dip

10.2.6 Serviceability Checks

Standard 625 Appendix G of the CARs requires that an aircraft's compass be swung and checked for serviceability following a lightning strike. Otherwise an annual "swing" (see section 10.2.7) is considered adequate.

10.2.7 Compass Swinging

In an aircraft, a compass is influenced by the magnetism of the aircraft's metal construction. This causes the needle to point in the wrong direction. The error is called *deviation* and should not be confused with *declination*—another name for variation.

Since a compass' deviation can never be completely removed, it is *swung* (i.e, checked for accuracy) annually and following certain occurrences such as a lightning strike on the aircraft.

There are various methods used to swing compasses. The simplest is to use an accurate compass rose painted on the ground and, with the aircraft's engine running and radios turned on, to align the aircraft with magnetic north and adjust the compass' north/south adjustment screw so that the compass reads north.[8] Once this adjustment has been made, the aircraft is turned to south and the compass is again adjusted, this time to remove half the error. The aircraft is then turned back to north and half the error is again removed. This process continues until the errors are small and constant.

[8] All adjustments are carried out with a non-ferrous (e.g., plastic or brass) screwdriver.

The same procedure is then followed for east and west headings, the compass' east/west adjustment screw being used.

When the difference between the compass' reading and the correct heading has been determined for every 30° (for example, indicating that to fly a heading of 270°, the aircraft should be turned until the compass is reading 268°), this correction is recorded in the aircraft's log book and is written on a card placed near to the compass.

10.2.8 Ground Check of Compass

Compass headings should be checked on the ground, particularly when lining up on a departure runway. Such a cross-check not only enables the pilot to check the accuracy of the compass but also to verify that the correct runway is being used. Accidents have occurred when a departing aircraft taxied onto the wrong runway, an example being Comair Flight 191, (Delta Air Lines Flight 5191) on 27th August 2006 at Blue Grass Airport in Kentucky. The aircraft was assigned runway 22 but used runway 26 instead. Runway 26 was too short and the Regional Jet overran the end.

The example given of the runway incursion at Providence, Rhode Island described in appendix B.1 on page 341 would also have been avoided had the pilots used their heading indicator or magnetic compass while taxiing.

10.3 Gyroscopic Instruments

Gyroscopes in aircraft instruments come in two types: the solid-state gyroscope, and the classical, mechanical gyroscope. Instruments based on the classical gyroscopes are being phased out, being replaced by Attitude and Heading Reference Systems (AHRSs) which use solid-state devices to provide aircraft orientation; see section 10.5.1. AHRSs provide three-axis information that can be displayed on "glass cockpit" primary flight displays (PFDs).

The solid-state and conventional gyroscopes are described in the sections below.

10.3.1 The Solid-State Gyroscope

Solid-state gyroscopes have no moving parts (other than a beam of light). They operate on the *Sagnac Effect*, named after the physicist Georges Sagnac. This effect occurs when a beam of laser light is split into two and the two parts are sent around a ring in opposite directions—see figure 10.21. The ring may be a physical ring made of many turns of optic fibre (known as a *ring interferometer*) or it may be a logical ring made up of numerous mirrors (known as a *ring laser*).

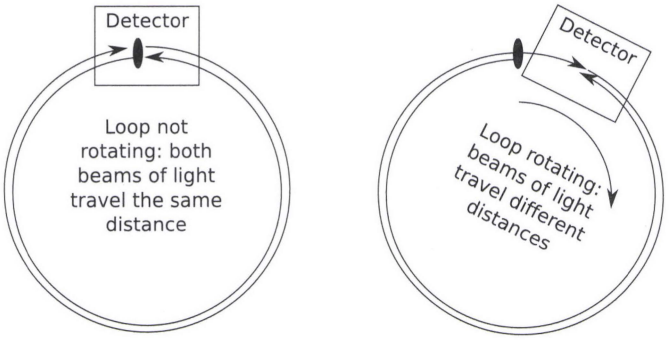

Figure 10.21: The Solid State Gyroscope

Imagine a ring interferometer being laid horizontally in an aircraft. When the aircraft is not moving, the beams of light passing around the loop will travel the same distance. If the aircraft were to start turning, then as shown on the right of figure 10.21, one beam would travel very slightly further than the other: the beam travelling in the direction of the turn would travel further than the one travelling opposite to the direction of turn. This difference in distance can be measured by the way the two beams interfere when they are combined, and a microprocessor can deduce how quickly the aircraft is turning.

The ring laser works similarly except that the pattern of interferences is detected across the whole ring.

It may be surprising that the difference in distance can be measured, because the rate of turn of an aircraft is negligible compared with the speed of light. However, multiple turns of fibre optic cable are used to create a light path of several kilometres and changes in interference can be measured very accurately. In fact, a solid-state gyro can detect rotation as slow as 0.00001° per hour (about 4,000 years for a single rotation!).

Solid-state gyroscopes are extremely sensitive and reliable as they have no moving parts and therefore no inertial resistance to movement.

10.3.2 The Classical Gyroscope

In contrast to the solid-state gyro, a conventional gyroscope has a moving part: a heavy disc spinning about its axis (see figure 10.22). The gyroscope has a long history—children's tops have been traced back to the early middle ages in England—and most people have, at some time, played with a child's gyroscope or top.

The first serious use of a gyroscope was probably Léonon Foucault's experiment in 1852 to demonstrate

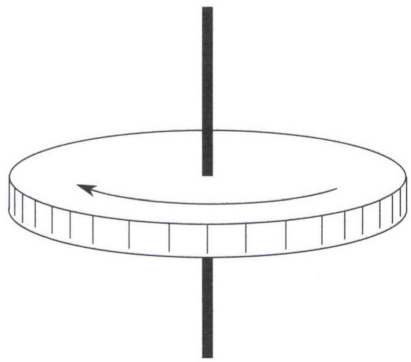

Figure 10.22: A Simple Mechanical Gyroscope

the rotation of the Earth.[9] The experiment didn't actually work because friction stopped Foucault's gyroscope after only about 10 minutes, too short a time to detect the earth's movement.

Principle of Operation.

Anecdote 31 *To demonstrate the practical use of a gyroscope in class, I take a toy gyroscope and, without setting it spinning, toss it to someone a few metres away. As expected, it tumbles as it flies through the air. Then I repeat the exercise after having set it spinning. This time it remains upright while flying through the air.*

The behaviour of the gyroscope in anecdote 31 is sometimes referred to as the gyroscope's "rigidity in space" but this is actually a misnomer: the gyroscope does *not* resist motion in space, it is just that the motion is not in the direction that common sense leads us to expect!

This operation of a gyroscope is difficult to explain using pictures and text on a 2-dimensional page. Two explanations are given below: one intuitive and one mathematical. The mathematical explanation does not need to be understood for the Transport Canada examination.

Gyroscope: Intuitive Explanation

This gyroscopic principle is obvious to anyone who has ridden a bicycle. Sitting on the seat, look at the front wheel while riding along. This is, of course, a gyroscope. Consider what happens when you want to turn left.[10]

[9] This experiment gave the device its modern name: rotation (Greek *gyros*) to see (Greek *skopeein*).

[10] This is best performed without your hands on the handlebars, but be careful!

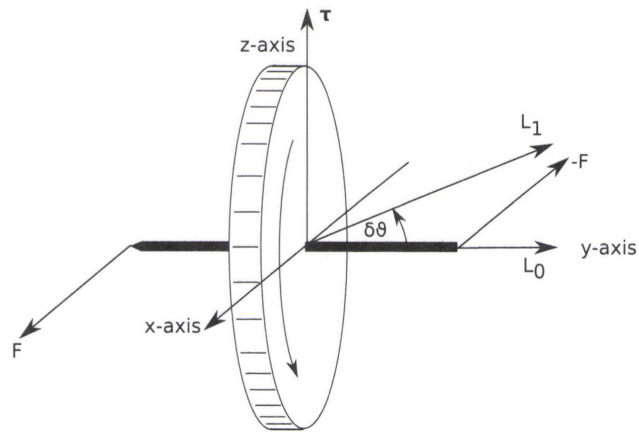

Figure 10.23: The Forces Acting on a Gyroscope

You lean the bicycle over slightly to the left. Rather than causing the bicycle to fall over, this causes the front wheel to turn to the left. This unexpected motion is known as *precession* and, as is explained in the next section, is simply a way of preserving the momentum of the wheel.

In general, if a heavy wheel (e.g., a bicycle wheel) is spinning then it has a certain inertia, the tendency to avoid stopping. If a force (more strictly a *torque*) is applied to the gyroscope (a torque to move the top of the wheel to the left, for example) then the gyroscope will tend to move at right angles to both the axis of spinning and the applied torque; the wheel will turn to the left.

Gyroscope: Mathematical Explanation

Consider the gyroscope in figure 10.23. It is assumed to be spinning around the y-axis. Clearly its angular velocity is in the direction of the y-axis and therefore, so is its angular momentum. When any change is made to the direction of the y-axis, that angular momentum will need to be conserved in some way.

Once the gyroscope is spinning around the y-axis, assume that it rotates slowly around the x-axis at an angular speed of Ω as illustrated in figure 10.23. After a short time, Δt, it has moved through a small angle $\delta\theta$ as illustrated.[11]

Since the rotation around the x-axis is slow, it changes the total angular momentum of the gyroscope very little. This means that, while the angular momentum has not changed in magnitude, it has changed in direction: from L_0 to L_1. The magnitude of the change is given by $\Delta L = L_0 \delta\theta$. The torque is the rate of change of angular momentum so

$$\tau = \frac{\Delta L}{\Delta t} = \frac{L_0 \Delta\theta}{\Delta t} = L_0 \Omega \qquad (10.5)$$

[11] This is equivalent to the bike wheel leaning over.

When the direction of the various vectors is taken into account, this can be written as

$$\vec{\tau} = \vec{\Omega} \times \vec{L_0} \tag{10.6}$$

Since $\vec{\Omega}$, lying along the x-axis, and $\vec{L_0}$, lying along the y-axis, are both horizontal, this means that $\vec{\tau}$ must be vertical, as shown in figure 10.23. To produce such a torque, horizontal forces, labelled $\vec{F}$ and $-\vec{F}$ have to be applied.

Thus, when we apply a torque to a gyroscope, the direction of motion ($\delta\theta$) is at right angles to the forces ($\vec{F}$ and $-\vec{F}$) producing the torque. This motion is known as *precession.*

Inertia

The inertia of a gyroscope (its resistance to change of its momentum) is determined by the mass of the rotating disc and how quickly it is rotating. A massive disc rotating quickly has more inertia than the same disc rotating slowly or a less massive disc rotating at the same speed.

Precession

The concept of precession is explained above—it is the motion induced at right angles to the applied torque.

There are several gyroscopes in a propeller-driven, fixed-wing aircraft (and even more in a helicopter) including those in the gyroscopic instruments (typically the heading indicator, the attitude indicator and the turn co-ordinator), the weather radar and the propeller itself. All of these are, by their nature, subject to precession.

With an understanding of precession, the apparent "rigidity in space" of the toy gyroscope in anecdote 31 can be understood. As the spinning gyroscope is thrown across the room, the motion of being thrown would naturally impart tumbling (as happens with the non-rotating gyroscope). This tumbling is a rotation, and because the actual motion of the gyroscope is at right angles to both the tumbling and the axis of spin, the gyroscope does not actually tumble. This can be seen with a toy gyroscope very easily. Consider figure 10.24. When the tip of the spinning gyroscope is released, it initially starts to fall, as would be expected. The force of gravity causing the gyroscope to fall applies a torque and, by the principle of precession, the gyroscope moves off in a direction at right angles to both gravity and the axis of spin.

There is a story, possibly apocryphal but too good to waste, from the early days of computing when a computer was first mounted in an aircraft. In those days, rather than the discs with which we're familiar, external storage was provided by a "drum": a very large, very heavy, rotating cylinder of metal. All apparently went well until the aircraft tried to bank...

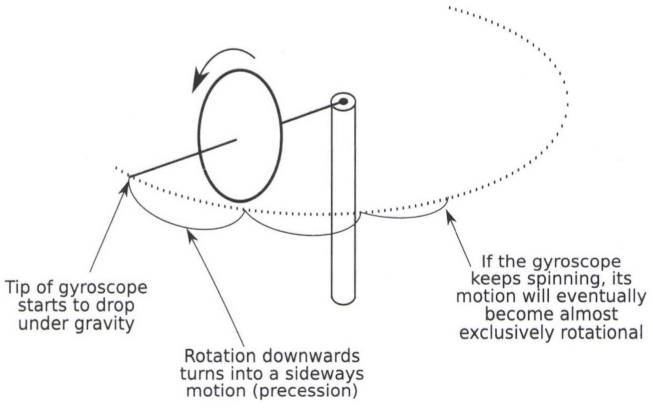

Figure 10.24: Gyroscopic Precession

10.3.3 Heading Indicator

Principle of Operation

The heading indicator (sometimes called the *Directional Gyro* or, in the UK, the *Directional Indicator*) as a separate instrument (rather than as part of an AHRS) consists of a gyroscope with its rotational axis along the horizontal (longitudinal) axis of the aircraft: the spinning disc is vertical. The disc spins at about 10,000 to 18,000 rotations per minute. When the aircraft turns about its vertical axis (i.e., to the left or right), the torque applied to the gyroscope, as described above, does not cause the gyroscope to turn *in that direction.* The gyroscope therefore appears to remain stationary in space as the aircraft (and the case of the heading indicator) turns around it. The motion of the case relative to the gyroscope is displayed on a compass card.

Unlike the magnetic compass, the heading indicator has no direction-seeking mechanism of its own; it must be set before the beginning of the flight, and will display changes in direction thereafter.

Most heading indicators have a so-called "heading bug" that can be manually adjusted. This makes a useful *aide-mémoire* for the pilot. When ATC issues an instruction to fly a particular heading, then the heading bug can be set to remind the pilot and, if the autopilot is coupled to the heading indicator, it will fly the heading indicated by the bug.

Errors/Malfunctions

The main errors of the gyroscopic heading indicator are caused by precession. Friction in the bearings of the gyroscope is the main cause of precession although the earth's rotation also contributes, particularly in a flight

with a significant change in latitude. The contribution to precession by the earth's rotation is proportional to the sine of the latitude and is therefore greater at the poles (where $\sin(\theta) = \pm 1$) than at the equator (where $\sin(\theta) = 0$). As the earth moves 15° per hour, unless the heading indicator is compensated, the drift caused by the earth's rotation at, say, 43°41′ N (the latitude of Toronto) will be $15 \times \sin(43.6833°) \approx 10.4°$ per hour. In Inuvik, at 68°18′15″ N, the precession in the heading indicator is 14° per hour.

Some aircraft owners who normally fly around one particular latitude have their heading indicator set for that latitude to reduce precession. This is achieved by adjusting the so-called *latitude nut* inside the heading indicator, something that can only be carried out on the ground in a maintenance facility. Most heading indicators in North America are shipped with the latitude nut set for 45° North.

Precession is seen on the display as a slow "drifting" of the heading. In the northern hemisphere the precession caused by the earth's rotation tends to cause the heading indicator to under-read (i.e., display a heading less than the correct one); in the southern hemisphere it causes it to over-read.

Precession means that, from time-to-time during flight, you need to reset the heading indicator. In most parts of Canada you do this by aligning the heading indicator with the magnetic compass during straight-and-level flight. In areas where the magnetic compass is unreliable, the heading indicator can be set to a true (rather than magnetic) bearing taken from the position of the sun or stars or, more practically, to a track read from a GPS (see section 6.2.6 on page 118).

Limitations

Gyroscopic heading indicators are subject to the "tumbling" problem described in *Limitations* on page 218 if limits of bank or pitch are exceeded. The limits are commonly 55° for either bank or pitch.

Anecdote 32 *It is not only aircraft gyroscopes that tumble in extreme pitch or bank situations. In 2007 I took a freighter across the North Atlantic from Montreal to Liverpool. Early one morning we were hit by a large wave that caused the very large (by aviation standards) ship's gyroscope, that controls the ship's autopilot, to tumble. The ship sailed in circles until it was reset.*

Power Sources

The gyroscope within the heading indicator is spun either electrically or by using air from a vacuum or pressure pump (see section 13.5.4 on page 302). When air is used, it is blown against numerous small indentations ("buckets") on the outside of the rotating disc.

Some heading indicators have some compensation for precession. As shown in figure 10.25, incoming air is divided into two parallel jets at the tip of the nozzle. Normally, the jets strike the buckets symmetrically and simply spin the disc. When the gyroscope precesses, both jets strike one side of the buckets and this asymmetry causes the disc to realign again.

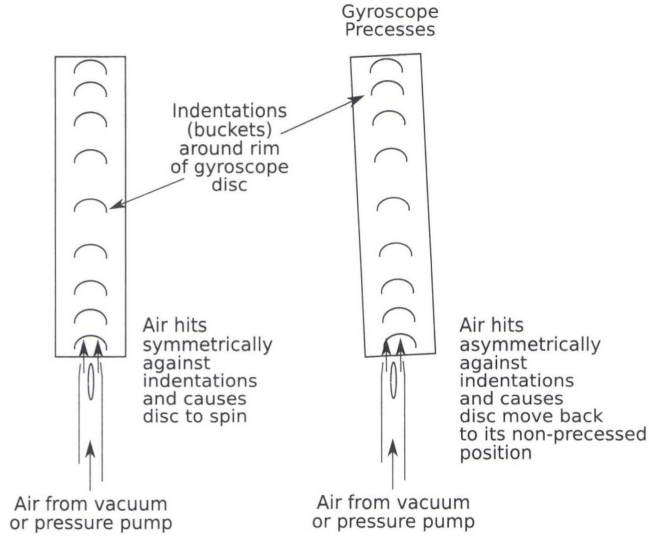

Figure 10.25: Compensating for Precession

Slaved Compass System

To avoid the pilot having to reset the heading indicator periodically to correct for precession, some heading indicators are "slaved" to a sensor (called a "flux gate" or "flux valve") that measures the earth's magnetic field. A servo[12] mechanism constantly corrects the heading indicator.

10.3.4 Horizontal Situation Indicator

A horizontal situation indicator (HSI) is a gyroscopic instrument that combines a heading indicator with a radio navigation receiver. Given this combination, it could be described either under *Flight Instruments* or *Navigation*. The decision was made to include it as a

[12] A servo is a system that incorporates an electric motor and a self-correcting positioning component.

navigation device, and its description will be found in section 7.5 on page 142.

10.3.5 Attitude Indicator

The first proposal for a gyroscopic attitude indicator dates from the 1740s. John Serson, an English scientist, suggested that sailors could use the stability of a gyroscope as an artificial horizon on ships. Unfortunately, when Serson went to sea to test this idea in 1744 the ship sank, and everyone drowned.

The attitude indicator (or *artificial horizon*) provides exactly what its second name suggests: a line on the face of the instrument aligned with the external horizon. When the pilot is flying in or above cloud, this artificial horizon can be used instead of the real one. It should be noted that, in this respect, it presents information in a different way from the turn co-ordinator (section 10.3.7). In the attitude indicator, the image of the aircraft's wings remains fixed and the horizon moves; in the turn co-ordinator the aircraft's wings move and the horizon remains fixed. This can cause dangerous confusion when, following a vacuum failure, the pilot has to switch from using the attitude indicator to using the turn co-ordinator as a primary instrument.

The attitude indicator shows pitch by the movement of the horizon bar up or down relative to the miniature aircraft. It shows bank by rotating the horizon bar against a scale, normally spaced at 10° intervals up to 30° and then at 60° and 90° positions.

Principle of Operation

The attitude indicator as a separate instrument (rather than part of an AHRS—see section 10.5.1) is a gyroscopic instrument, but, increasingly, the gyroscope is not a mechanical rotating gyroscope: see the solid-state AV-30 device in figure 10.26 which displays not only attitude information, but also heading, airspeed, inclinometer and altitude.

When the attitude indicator contains a mechanical gyroscope, that gyroscope is mounted with its spin axis vertical and it normally has a "self-erecting" system whereby the axis is kept vertical by gravity: movement away from the vertical being automatically corrected at 3° per minute.

The gyroscope is connected mechanically to the horizon bar of the display (B in figure 10.27). As the aircraft banks the horizon bar moves to reflect the real horizon out of the front window of the aircraft. In figure 10.27, for example, the right wing of the aircraft (labelled C) is below the horizon and the aircraft is therefore banking to the right. The amount of bank can be read from the marker (labelled A): 20° in this case.

Figure 10.26: A Solid State Attitude Indicator

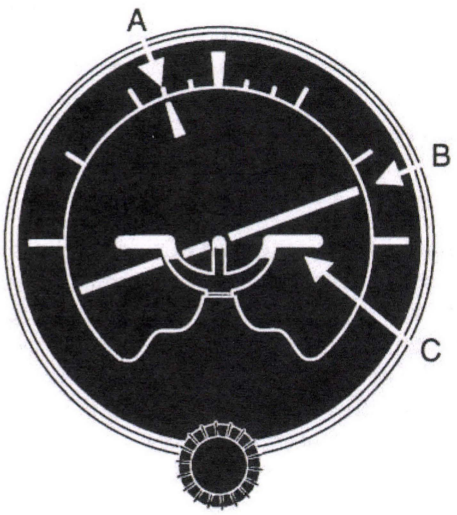

Figure 10.27: The Attitude Indicator Display

Pitch is displayed by showing the nose of the aircraft (the white dot in the centre) above or below the horizon. In figure 10.27, for example, unless the aircraft is accelerating or decelerating, it is neither climbing nor descending since the tip of the aircraft symbol is on the (artificial) horizon.

Errors/Malfunctions

During a co-ordinated turn, the torque caused by the turning forces causes the gyroscope to precess toward the inside of the turn. This increases as the bank steepens and disappears as the aircraft rolls out to level flight. For this reason, particularly when performing a steep turn, the attitude indicator can be used for rolling into and out of the turn but other instruments should be used during the turn itself.

Perhaps the most dangerous error of the attitude indicator is its inability to distinguish between acceleration and pitch up: see *The Somatogravic Illusion*

on page 46. When the aircraft accelerates, the attitude indicator indicates a pitch up, and this can seriously mislead a pilot who fixates on this one instrument. The typical condition is a take-off into very dark conditions. If the aircraft's nose is allowed to drop slightly, the aircraft accelerates and the attitude indicator shows a nose-up attitude. The pilot, if only looking at the attitude indicator, may try to correct this by lowering the nose. This causes more acceleration and a larger nose-up attitude display. This continues until the aircraft flies into the ground. Of course, the problem can be avoided if the pilot cross-checks the information from the attitude indicator with that from the altimeter, vertical speed indicator and airspeed indicator.

If the attitude indicator fails (perhaps because the electrical or vacuum system driving it has failed), it will "flag": a flag appears indicating that its reading cannot be trusted. In stressful situations, it is easy to overlook these flags and continue to follow a failing attitude indicator into a spiral dive.

Limitations

The primary limitation of the attitude indicator is that, by its design, it displays the pitch angle of the aircraft relative to the external horizon. It is much more useful for a pilot to know the aircraft's angle of attack but this is not displayed and has to be inferred from the attitude indicator and other displays (airspeed indicator, altimeter, vertical speed indicator).

Another limitation, particularly of older attitude indicators, is the maximum angle of bank and pitch that can be accommodated before the gyroscope "tumbles": precession taking the gyroscope beyond the point from which it can spontaneously recover. This can damage the bearings of the gyroscope as well as rendering it useless until manually erected again after the flight. Some attitude indicators have mechanisms to hold the gyroscope's mounts in place, and activating these is known as *caging the gyro*. Even though caging causes greater than normal wear, older gyroscopes should be caged during aerobatic manoeuvres to avoid damage to the instrument.

Because the axis of gyroscope is vertical (the disc rotating in the horizontal plane), an attitude indicator cannot detect or display yaw: only pitch and roll.

Power Source

The attitude indicator is normally powered either by electricity or from the aircraft's vacuum system.

10.3.6 Turn & Slip Indicator

Principle of Operation

Figure 10.28: Turn and Slip Indicator

The turn and slip indicator, like the turn co-ordinator (section 10.3.7), is really two instruments in one: a gyroscopically driven device that indicates a turn around the aircraft's vertical axis and the *inclinometer* or *co-ordination ball* that indicates whether the aircraft is skidding, slipping or in co-ordinated flight.

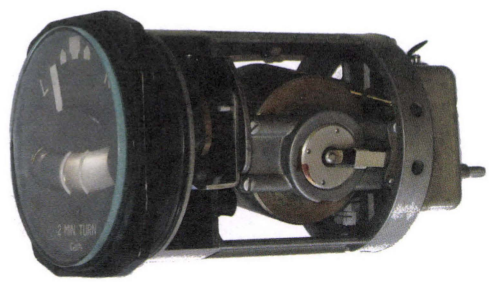

Figure 10.29: Gyroscope in a Turn and Slip Indicator

As can be seen from figure 10.29, the gyroscope within a turn and slip indicator is mounted so that its rotational axis lies across the aircraft (parallel to the wings). This means that it is sensitive only to the aircraft turning about its vertical axis. In particular it does not register any motion as a result of rolling unless the roll also makes the aircraft turn.

Anecdote 33 *I often apply a battery to the turn and slip indicator in figure 10.28 during a ground school class. It surprises many students when, having set the gyroscope spinning, I rotate the unit as though it were in a banking aircraft. The needle does not move. If a pilot turns an aircraft by using the rudder, keeping the wings level, the turn and slip indicator registers this. If a pilot rolls the aircraft without it turning, the turn and slip indicator registers nothing.*

The turn indicator, as illustrated in figure 10.28 consists of a single needle that points directly upwards if the aircraft is not turning. Otherwise it indicates a turn to the left or right. Two white marks are normally drawn on the face of the display, indicating a rate one turn: a turn that takes 2 minutes to complete.

The inclinometer is perhaps the simplest instrument in the aircraft: it consists of a small ball mounted in a tube filled with a damping liquid. If the aircraft is in completely co-ordinated flight (i.e., is neither slipping nor skidding) then the ball is in the middle. Otherwise it indicates unco-ordinated flight. Figure 10.30 illustrates the inclinometer display in co-ordinated flight and in the two extremes of slipping and skidding. Pilots are told to "tread on the ball" to correct unco-ordinated flight: in the left hand picture in figure 10.30 the pilot would tread on the right pedal because the ball is to the right.

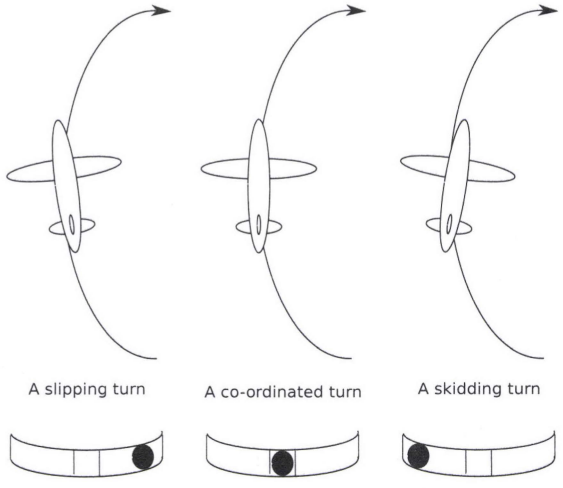

Figure 10.30: Inclinometer Display

Errors/Malfunctions

Apart from the mechanical failure of the gyroscope or the failure of the power source, a turn indicator has no significant intrinsic causes of error or malfunction.

Limitations

The primary limitation of the turn indicator is also its greatest strength: it displays exactly one thing accurately—turn. It might be expected to indicate bank (as a turn co-ordinator does) but it does not. Some pilots prefer a turn indicator to a turn co-ordinator (and, in most cases, a second attitude indicator to either) because its display is "honest" whereas that of a turn co-ordinator "confuses" bank and turn.

Power Sources

The turn and slip indicator is normally powered by electricity.

Exercise 86 *A pilot wishes to turn right from a heading of 320 to a heading of 080 in a rate one turn. Her heading indicator has failed and she needs to make a timed turn. For how long should she turn?*

10.3.7 Turn Co-ordinator

Principle of Operation

In some ways, the turn co-ordinator (see figure 10.31) can be seen as an improvement on the turn and slip indicator since it displays roll (rotation about the longitudinal axis) as well as yaw (rotation about the vertical axis). This is achieved by having the gyroscope mounted up at about 30° around the lateral axis.

Figure 10.31: Turn Co-ordinator Display (Mysid)

The inclinometer in a turn co-ordinator is the same as that in a turn and slip indicator—see section 10.3.6.

Errors/Malfunctions

Other than the failure of the gyroscope or its power supply, the turn co-ordinator does not have any significant intrinsic errors.

Limitations

The major limitations of the turn co-ordinator are:

- that it does not display changes in pitch so cannot totally replace an attitude indicator
- that it does not clearly display either roll or yaw: it confuses the two. As an aircraft rolls into a turn, the turn co-ordinator registers both the roll and the

turn. As the aircraft becomes established in the turn, the roll rate becomes zero and the turn co-ordinator only displays turn. This can be confusing.

To emphasise the first of these points, as the turn co-ordinator becomes a primary instrument if the attitude indicator fails, many turn co-ordinators have a label stating *No Pitch Information.*

From a human factors point of view, the primary disadvantage of the turn co-ordinator is that it displays information in a manner completely contradictory to the attitude indicator: the former displays a static horizon and tilting aircraft, the latter a tilting horizon and static aircraft. For this reason, many pilots prefer to have a second attitude indicator (electrically driven) rather than an attitude indicator and a turn co-ordinator.

Power Sources

The turn co-ordinator is normally powered by electricity.

10.4 Collision Avoidance

The Traffic Collision Avoidance System (TCAS) and Automatic Dependent Surveillance – Broadcast (ADS-B) systems both have the same aim—to allow the pilot of one aircraft to know that another aircraft is flying in the vicinity.

10.4.1 TCAS

TCAS Operation

TCAS relies on aircraft having transponders that, when interrogated, respond with the altitude of the aircraft.

An active TCAS device, as fitted to most commercial aircraft, transmits an interrogation signal in the same way as ATC's secondary radar[13] and receives the responses. This allows the positions and altitudes of all responding aircraft to be displayed in the cockpit.

More sophisticated TCASs, known as TCAS-II, additionally provide advice to the pilot (e.g., "Climb immediately") and co-ordinate the messages in the two merging aircraft so that one pilot may be told to descend while the other is told to climb. It is believed that the midair collision on 1st July 2002 between Bashkirian Airlines Flight 2937 and DHL Flight 611 over Überlingen in Germany was caused when one pilot obeyed the TCAS command to descend while the other ignored the TCAS command to climb and, under instructions from ATC, also descended. This incident led to the European Joint Aviation Authorities (JAA) issuing instructions that a TCAS instruction may only be ignored if the potentially conflicting aircraft have each other in sight.

Passive TCAS devices, which are increasingly common as portable units in light aircraft, do not transmit interrogation signals but rely on over-flying commercial aircraft or ATC's ground radar to do so. The devices eavesdrop on the responses and display the direction, altitude and an estimation of the range of other aircraft. The range of passive TCAS devices is typically limited to 7 to 10 nautical miles and so is really only suitable for slow aircraft.

TCAS Weaknesses

The major drawback of TCAS is that it relies on all aircraft having working transponders—an aircraft flying without a transponder is effectively invisible and one with a transponder transmitting false altitude information (see anecdote 30 on page 209) is dangerous. The drawback of the passive TCAS devices is that they additionally require some nearby station to be transmitting interrogation signals and, as they don't transmit the interrogation themselves, they cannot accurately measure range.

10.4.2 ADS-B

ADS-B Operation

In August 2023, Automatic Dependent Surveillance — Broadcast (ADS-B) became mandatory in Canadian Class A airspace. As of May 2024, ADS-B became mandatory in Canadian Class B airspace. Mandates for Canadian Class C, D and E airspace will become effective no earlier than 2028. ADS-B is used and is mandatory in some classes of airspace in the USA.

The concept of ADS-B arose from the observation that most aircraft are equipped with GPS and can therefore determine their own position and altitude very accurately. Rather than using a ground-based secondary radar system to interrogate a transponder in the aircraft every 5 to 12 seconds, why not have an aircraft transmit its own position every second? If each aircraft were to do this, then other aircraft in the area could receive those signals and the ADS-B device could calculate the relative distances and heights to determine whether another aircraft presented a hazard.

The elements of the ADS-B acronym make some sense:

- **Automatic:** aircraft *automatically* report their position, without radar interrogation

[13] Note that secondary radar is not "radar" in the normal usage of the word: it is a radio conversation between the ground station and the transponder in the aircraft.

- **Dependent:** the system *depends* on each aircraft having an approved WAAS GPS on board
- **Surveillance:** it is a *surveillance* system that shows ATC the position of aircraft
- **Broadcast:** aircraft *broadcast* their position to other aircraft and to ATC

There are two parts to an ADS-B system in an aircraft: ADS-B Out and ADS-B In.

ADS-B Out periodically transmits an identification, the aircraft's position, altitude, speed and direction of flight. This can be received by satellites and ground stations to give controllers position information that is more accurate than traditional secondary radar. It can also be received by other aircraft if they are equipped with ADS-B In functionality.

ADS-B Out in an aircraft is primarily of use to other aircraft and controllers, and, after 1st January 2020, a panel-mounted, certified ADS-B Out device is mandatory in all aircraft flying in what was previously transponder airspace in the USA.

ADS-B In allows the aircraft to receive information about nearby aircraft from ground stations (known as the *Traffic Information Service – Broadcast, TIS-B*) as well as ADS-B Out signals directly from nearby aircraft. Depending on the sophistication of the unit, it may display a map of where other aircraft are, or may perform path prediction and alert the pilot to potential near-misses.

There is no requirement to have ADS-B In in an aircraft in USA airspace.

In the USA, two frequencies are used for the ADS-B transmissions: 1090 MHz for aircraft that operate above 18,000 ft ASL and 978 MHz for aircraft that operate exclusively below 18,000 ft ASL. It is likely that Canada will require 1090 MHz operation for all aircraft, making it difficult to purchase cheap devices from the USA for small, general aviation aircraft.

Once a 978 MHz ADS-B In unit is fitted in an aircraft, it can also be used to receive and display weather, NOTAM, ATIS and other useful information from the *Flight Information Services – Broadcast, FIS-B*. It is intended that eventually this will become a two-way information exchange, with the aircraft transmitting weather data collected by sensors on the aircraft.

ADS-B in the North Atlantic

The description above indicates that ADS-B Out signals from an aircraft are picked up by ground stations and by other aircraft. They may also be received by low earth orbit (LEO) satellites.

This is particularly useful when the aircraft are out of range of normal secondary radar (i.e., transponder interrogation), such as crossing the North Atlantic. On such routes, the spacing between aircraft has to be large because the precise relative positions of the aircraft are not known. If all aircraft flying these routes were equipped with ADS-B Out, and these signals were made available to controllers through satellite reception, then reduced spacing could be used, and aircraft could have the flexibility of changing altitude to avoid turbulence or catch a tailwind.

It is expected that, eventually, all ground stations will be removed and the ADS-B system will become satellite-based.

ADS-B Weaknesses

One of the major weaknesses of ADS-B is that there is no security on the transmissions. The hardware and software needed to build a non-certified, handheld ADS-B In unit is very simple; pre-built boards are available for most cheap, embedded computers such as the BeagleBone, Arduino or Raspberry Pi. At the Black Hat Conference in 2012 Andrei Costin demonstrated how ADS-B Out signals could be spoofed using a $1,000 soft radio. The lack of security also means that sensitive commercial information is leaked about the tracks of business jets.

10.4.3 TCAS & ADS-B

Both TCAS and ADS-B rely on co-operation from the target aircraft: in the case of TCAS it is the transponder's response to an interrogation, in the case of ADS-B it is the ADS-B Out signal sent periodically by the aircraft. An aircraft without the necessary equipment is effectively invisible.

The future lies with ADS-B. ICAO considers ADS-B in the first of its "Aviation System Block Upgrades" to be the system to provide the "capability for ground surveillance" and the system to allow "improved access to optimum flight levels".

10.5 Miscellaneous Instruments

10.5.1 Attitude Heading Reference System (AHRS)

An AHRS consists of 3-axis sensors that provide heading, attitude and yaw information. The information provided by the AHRS is fed to a computer that

generates heading and attitude instruments for display on a Primary Flight Display.

The technology used within an AHRS may be solid-state or Microelectromechanical (MEMS)[14] "gyroscopes", accelerometers and magnetometers. In addition, some AHRSs use signals from the GPS receiver to improve the long-term stability of the readings.

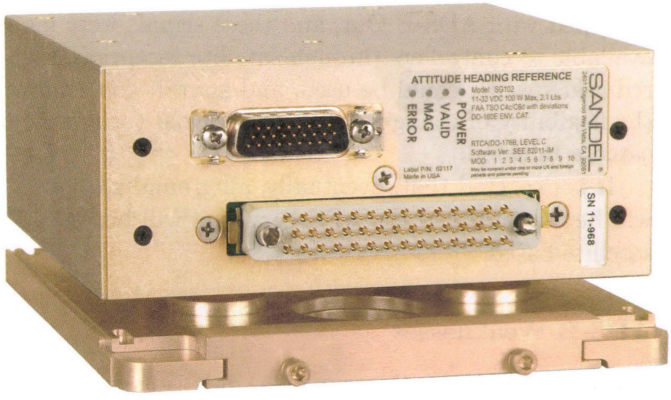

Figure 10.32: A Sandel SG102 AHRS (Sandel Avionics)

Generally, an AHRS is simply a box of electronics with ports to receive external signals (e.g., GPS, static pressure) and to drive a display—see, for example, figure 10.32.

The primary advantages of AHRSs over traditional gyroscopic instruments are:

- their **ruggedness.** The SG102 shown in figure 10.32 is designed for helicopter operation where vibration is intense. As there are no moving parts, the mechanism is insensitive to vibration although the mounting may still require isolation mounts as shown in the figure.
- their **size.** The SG102 measures 12.7 cm × 13.7 cm × 6.1 cm and weighs only 1 kg.
- their **flexibility.** An AHRS can be mounted anywhere in the aircraft; it does not have to be mounted at the instrument panel.
- their **life expectancy.** As they have no moving parts, they should, in principle, never wear out.
- their **accuracy.** As mentioned above, AHRSs can measure and display tiny movements.

[14] You may be familiar with MEMS accelerometers because they are used in cellular telephones to provide movement information.

10.5.2 Radio/Radar Altimeter

Purpose

Radar altimeters give very precise measurements of the height of an aircraft *above ground* (rather then above sea level) and are used in a number of aircraft applications:

- In ground proximity warning systems (GPWSs), warning the pilot if the aircraft is flying too low. Note that radar altimeters do not detect terrain ahead of the aircraft, only that directly below it, and so cannot give a warning if the aircraft is flying over a flat plain towards a mountain.
- In landing gear warning systems, warning that the aircraft is low with its wheels still up.
- During category III ILS (autoland) approaches. Because there is no decision height on this type of approach, an accurate measurement of height above ground is essential. Again, this application suffers from the radar altimeter's measurement of height above ground rather than height above sea level: on the ILS approach to runway 18L at Cincinnati, USA, for example, aircraft cross a wide and deep valley (the Ohio River) just before the threshold, and the radar altimeter indication suddenly increases by 200' and then decreases again, even when the aircraft is on a stable glidepath.
- In controlling the sensitivity of auto-pilots. When an aircraft is flying low in the final stages of its approach, the auto-pilot may have to make larger flight surface deflections to compensate for instabilities.

History

Lloyd Espenschied invented the radar altimeter in 1924; the first commercial product was produced by the Western Electric Company in 1937.

Principle of Operation

A radar altimeter in an aircraft operates by transmitting a radio signal in the 4.250-4.435 GHz band directly towards the earth from the underside of the aircraft. The signal is actually a "chirp"—a signal continually changing in frequency (pitch)—repeated between 50 and 300 times per second. Using a chirp rather than a continuous signal allows Doppler shifts in the returned signal caused by the change in height of the aircraft to be corrected.

If the aircraft is sufficiently low (the precise height depends on the type of surface, but is typically about 2,500 ft from the ground) the aircraft receives the

reflected radio waves and calculates the distance they have travelled from the difference in frequency between the transmitted and returned waves.

Note that, unlike a barometric altimeter (section 10.1.4), a radar altimeter measures the height of the aircraft above the ground, not above sea level.

Limitations

Apart from measuring height above the ground rather than above a constant plane such as sea level, the radar altimeter has other limitations:

- Most radar systems use the same antenna for transmission and reception. The receiver is electronically blocked while the transmitted signal is sent. The transmitter is then blocked and the receiver unblocked to receive the reflection. With a radar altimeter, the delay between the signal being transmitted and the reflection being received is very short, so there is no time to turn the transmission off and the receiver on. This means that separate transmit and receive antennæ have to be fitted to the aircraft.
- The range of the radar altimeter depends on the type of ground over which the aircraft is flying. Bare rock and water reflect the signals well whereas tree cover reflects poorly.

10.5.3 Weather Information

Being able to obtain current weather information is of obvious importance to a pilot in flight. In the past the only way to do this was through voice contact with a Flight Service Station or by fitting weather radar in the aircraft. Weather radar was generally too bulky, heavy and expensive to be fitted into a light aircraft.

This is largely still true of weather radar but lightning detection systems and graphics transmitted from the ground to a display in the cockpit are now extensively used in light aircraft.

Uplink Weather Information

Probably the weather information system most used in light aircraft is having the various textual and graphical products that are used during a ground briefing (METARs, TAFs, GFAs, radar images, etc.) transmitted to the aircraft while it is in flight. These may be received by an ADS-B receiver or by a receiver sold as part of a commercial service.

Several private agencies transmit weather information from a ground station through a geo-stationary satellite and these can be received by an aircraft with a simple receiver and displayed on a laptop, tablet or a built-in display. Many GPS units display received images of heavy precipitation and lightning strikes on the moving map so that the pilot can quickly see the aircraft's position relative to the weather. Generally, the companies that provide this type of weather information do so for a monthly fee and, even then, not for the whole of Canada.

The major advantage of using radar pictures from the ground rather than from a radar in the aircraft is that the views can be constructed as composite pictures of many ground-based radars and that static objects (e.g., mountains) can be digitally removed; see section 5.3.3 on page 98. This gives the pilot a wider and more comprehensive view than that from a single radar in the aircraft. On-board weather radar, for example, might not see a very large thunderstorm cell masked by a less heavy, but closer, rainstorm. Ground-based radar pictures, with stations behind as well as in front of the storm, may be able to display both.

Another advantage of receiving ground-based signals is that they can combine lightning and heavy precipitation information. Equipment on board an aircraft will typically display one or the other.

One disadvantage of receiving ground-based weather data is the delay—sometimes images can be delayed by one or two minutes and, in that time, thunder cells can develop and surprise a pilot.

Weather Radar

Radio waves are reflected by various surfaces, including heavy rain. The concept behind weather radar, whether mounted in an aircraft or on the ground, is therefore simple: to emit a burst of radio waves and wait for a reflection. The time between the transmission and reflection gives an estimate of the distance to the reflecting object and the strength of the reflection gives an estimate of the type of object (mountain, light rain, heavy rain, etc.).

The transmitting and receiving antennæ are normally fitted into the aircraft's nose cone. This is unfortunate because, for the highest sensitivity, the antennæ need to be as large as possible and the nose cones on most aircraft are very constricted. To compensate for moderate movement of the aircraft, the antennæ are normally kept stable by means of a gyroscope—either a signal slaved from the aircraft's attitude gyroscope or from a separate gyroscope installed as part of the radar.

Weather radar operates in the x-band frequency range from about 8 to 12.5 GHz. Power output is either between 10 and 60 kW (high-power) or between 100 and 200 W (low power). The former can be dangerous to personnel when the aircraft is on the ground and requires complex and heavy power supplies. The latter

requires much more sophisticated electronics to extract the reflected signal from the surrounding electrical noise.

Turbulence Detection

For aircraft flying at high altitudes (typically above 23,000 ft ASL), clear air turbulence (CAT) is a particular hazard—see section 4.13.4. Aircraft can suffer structural damage if they encounter severe CAT and, in extreme cases, this has led to the break-up of the aircraft. Much more common is injury to crew and passengers when CAT is encountered. In a report in 2001, American Airlines estimated that injuries to its crew members caused by CAT was costing it 15,000 lost workdays per year. CAT is also the major cause of a fear of flying in potential passengers.

Since CAT is not marked by clouds and is not visible to normal weather radar (there being no precipitation), special devices known as *scintillometers* or *Doppler LIDARs*[15] have to be fitted to aircraft to detect CAT. LIDARs transmit 10 to 20cm diameter beam of laser light ahead of the aircraft. This light has a much shorter wavelength (2022.54 nm)[16] than radar signals and can therefore detect much smaller particles. Changes in the reflections from the very small particles in the atmosphere are measured using Doppler techniques: the changes in the frequency of the signal caused by the reflecting particle moving towards or away from the receiver. It is thereby possible to detect wind shear and give a prediction of potential CAT.

LIDAR devices are also used at airports to detect wind shear on approach and departure paths.

Lightning Detection

A class of detectors known as *sferics* can be mounted even in small aircraft to detect the electromagnetic discharges associated with lightning strikes.

These devices, the most popular being Strikefinders and Stormscopes, are mounted with the display on a dedicated instrument or as an overlay on a GPS moving map. Each time a lightning strike is detected, it is displayed as a dot on the screen. Figure 10.33 shows the ground-based radar and the Strikefinder display in an aircraft flying westwards across Lake Michigan, USA from Muskegon to Madison. The storm visible on the ground radar to the aircraft's left is clearly shown on the Strikefinder display.

One disadvantage of the sferic devices is that they require a degree of experience on the part of the pilot to interpret the information they are displaying. In particular their estimates of distance to the strikes are sometimes very imprecise. The direction of the lightning is easy to deduce using techniques similar to those of an ADF. Estimating the range is much harder and is done by comparing the "signature" of the lightning with storms in the device's database. This can cause a nearby weak storm to be displayed further away than it is, or an intense storm to be displayed closer than it actually is.

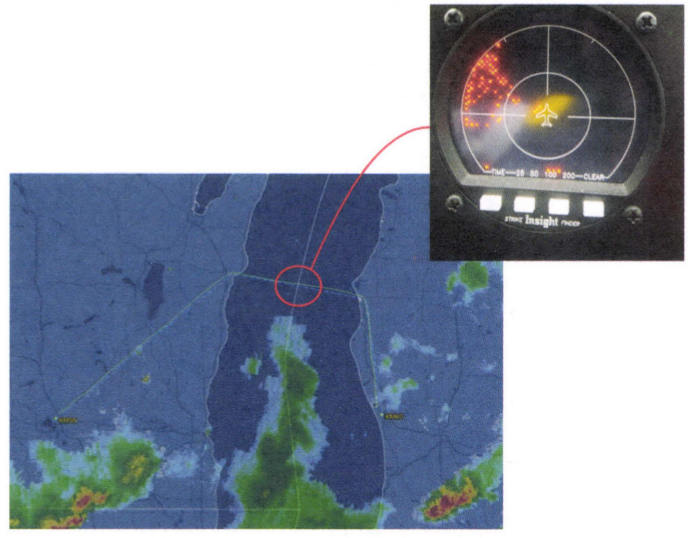

Figure 10.33: The Strikefinder Display

Anecdote 34 *Many years ago, while flying our Cessna 172 from Ottawa to Cincinnati, my wife and I were caught, in IMC, between two thunderstorms just south of Lake Erie. Without any form of weather information in the aircraft we had to rely on ATC's primary radar to guide us around the storms. ATC radar is not designed to display weather information and ATC has no obligation to pass on what is being displayed. In this case, a co-operative controller kept us safe. Within a couple of months of returning from that trip, we had the Strikefinder shown in figure 10.33 fitted. This has kept us out of trouble on many occasions.*

Sferics devices should not be thought of as a way of finding "holes" in lines of thunderstorms—that is obviously very dangerous. Instead, they display the big picture and allow deviations to be made in good time. This is one of the most useful investments we have made in our aircraft.

Radar Images & Thunderstorms

It is important to remember that radar images, whether from ground- or aircraft-based systems, display

[15] Light Detection and Ranging.

[16] This may be the only time in this book that *nm* refers to nanometres rather than nautical miles!

precipitation. The area where hail and rain are falling in a thunderstorm is often a significant distance from the area where the incoming air is rising: as described in section 4.15.1 on page 89 the most severe thunderstorms occur when there is a wind shear aloft. In this case the radar will show the area where precipitation is falling, which may be several miles away from where the inflow air will cause severe turbulence that could possibly destroy an aircraft.

10.6 Instrument Flying

Instrument flying is obviously a very big topic—see the *Instrument Procedures Manual* from Aviation Publishers. This section contains some very simple advice for VFR pilots encountering instrument conditions. It is included as it features in Transport Canada's Commercial Pilot Licence syllabus, but it should not be thought of as replacing IFR flight training.

10.6.1 Loss of Visual Reference

A pilot flying an aircraft in VMC relies on many senses to keep the aircraft upright; see section 2.11. The primary sense is sight of the horizon out of the window. When an aircraft enters cloud, this sense is effectively removed and pilots not trained to fly in instrument conditions often enter a spiral dive within a few minutes. Even pilots trained to interpret the instruments for orientation by using view-limiting devices often find encounters with genuine cloud disconcerting—there is a big difference between not being able to see (with a view-limiting device) and being able to see nothing (when in cloud). All pilots should insist on some hours in real cloud during their training.

The most important thing to remember if you enter cloud and are not familiar with instrument flying is that the aircraft doesn't fly any differently because it's in cloud. You should turn on the carburetor heat and the pitot heat if it's available, but otherwise the best advice is probably to do nothing, quickly!

10.6.2 Control/Performance Instruments

For training purposes the flight instruments can be divided into the control and the performance instruments. When in straight and level flight (which you want to maintain in the cloud):

The **control instruments** are the power indicator (tachometer and/or manifold pressure gauge) and the attitude indicator. As power setting changes only infrequently, the main control instrument is the attitude indicator — it is this instrument that determines the control inputs required.

The **performance instruments** are the altimeter, the airspeed indicator and the vertical speed indicator. These are used to ensure that the control inputs are giving the desired results.

10.6.3 Instrument Scan

Most experienced instrument pilots would probably find it difficult to describe their scan techniques. The scan covers all instruments looking not for their readings but for *changes* in their readings. The primary issue to avoid is fixation—staring exclusively at one or two instruments and neglecting the others. It is only by keeping the eyes moving that a failed instrument will be detected.

Another important factor is to avoid focussing on navigation instruments (VORs, ADFs, localisers)—such focus leads to continual turns "chasing the needle". Find a heading that keeps the needle centred (this is really easy if you have even a hand-held GPS to provide track, rather than heading, information) and scan the flight instruments, not the navigation instruments.

A suitable scan technique for learning instrument flying is one returning constantly to the attitude indicator: AI, ASI, AI, HI, AI, ALT, ... While doing this you will also see the VSI out of the corner of your eye: remember that you are looking for changes, not absolute values. Every tenth or so scan should include the oil temperature, oil pressure, vacuum pressure and the navigation instruments.

10.6.4 Aircraft Control

As stated earlier, the aircraft does not fly differently because it is in cloud and the pilot cannot see anything out of the window. Controlling the aircraft does not change except that, for keeping the aircraft level, the artificial horizon of the attitude indicator replaces the actual horizon.

One potentially hazardous maneuver is banking to change heading. It is here that control can be lost and a spiral dive entered. One possible technique is the one used by many pilots to make small turns when very close to a VOR or when flying a localiser. In these conditions, experienced pilots tend to use only the rudder to make the type of turns required. Turning with minimum bank like this may be a less dangerous way of turning when in cloud.

10.6.5 Partial Panel

The term "partial panel" refers to the instrument panel if a set of instruments, typically the vacuum

instruments, has failed. The critical issue is to determine that the failure has taken place—students in a simulator sometimes follow a failing attitude indicator into a spiral dive. A scan of the performance instruments should detect this promptly.

If a pilot rarely enters IMC, it is unlikely that an instrument failure will occur during that time. However, if such a failure *does* occur, then it must be treated as an emergency—declare an emergency unambiguously and ask for "non-gyro vectors". Many controllers are not pilots so do not assume that they will understand the urgency if you simply say that your vacuum system has failed. The term "non-gyro vectors" is a term in the controller's lexicon and will be understood.

With non-gyro vectors the controller will not assign headings ("fly heading 120") but will instead give instructions to "start turning left... stop turning... start turning right... stop turning". All turns should be flown at rate-one using the turn co-ordinator as reference.

One of the main challenges with flying partial panel is to disregard the failed instruments. Even when you know they have failed, there is an automatic tendency to refer to them. For this reason, it is a good idea to carry two soap-holders (suction cups) in your flight bag for covering failed instruments in flight. A couple of bent business cards could serve as well.

10.6.6 Unusual Attitudes

In instrument flight, stalls, spins and spiral dives are (reasonably!) considered to be unusual attitudes. A pilot suspecting that the aircraft is moving towards an unusual attitude again needs to remember that the aircraft does not fly differently because it is in cloud—whatever recovery technique works in visual conditions will also work in instrument conditions.

The first question is whether the aircraft is moving towards a stall/spin or a spiral dive. The airspeed indicator and vertical speed indicator allow these two conditions to be distinguished, and then the recovery technique specified in the pilot operating handbook can be applied.

10.7 Answers to Exercises

Exercise 80

Ignoring the conversion from IAS to CAS, 2% of 95 knots is 1.9 knots. Your true airspeed is then approximately

$$95 + (1.9 \times 8) = 110 \text{ knots}$$

In fact, on a standard pressure and temperature day, your true airspeed as calculated with an aviation calculator is 107 knots, so this calculation is reasonably accurate.

Exercise 81

The static port is attached to the altimeter, vertical speed indicator and airspeed indicator (see figure 10.3) and so all three will be affected.

- The altimeter and vertical speed indicator are connected only to the static port. Since the pressure in the static system is no longer changing (due to the blockage), neither instrument will indicate that the altitude is changing—the altimeter will simply remain unchanged and the vertical speed indicator will read zero.
- The airspeed indicator is measuring the difference between the pitot pressure (dropping as altitude is gained) and the static pressure (that should be falling, but is not, because of the blockage). The difference in pressure is therefore getting smaller and the value displayed on the airspeed indicator will be too low.

Exercise 82

The first part of this answer is that, since the airspeed indicator is the only instrument connected to the pitot tube (see figure 10.3), only it will be affected in any way. The airspeed indicator displays the difference in pressure between the pitot tube and the static port. During a descent, if the pitot tube were not blocked, the air pressure would be increasing at both the pitot tube and static port, keeping the difference (and therefore the displayed speed) more or less constant. With a blocked pitot tube, the pressure in the pitot system will remain at the lower pressure. The difference between this and the pressure at the static port will therefore decrease (the pitot pressure remaining the same, the static pressure rising) and the airspeed displayed will be too low.

Exercise 83

Figure 10.34 shows the situation. Since the aircraft is facing Polaris, it is facing true north. The magnetic variation at the airport is 20°W and so the magnetic north pole is 20° to the west of the true north pole as shown in figure 10.34. The compass is therefore pointing 20° east of the magnetic north—i.e., it is reading 020. The runway number is therefore 36T if the airport is in the northern domestic airspace where runways are oriented to true north or 02 if in the southern domestic airspace.

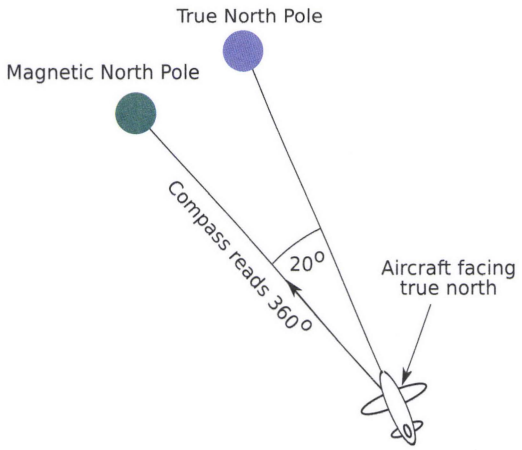

Figure 10.34: Diagram for Example 83

Exercise 84

Using a dip angle of 71.27° from figure 10.18 and equation 10.1 for the northerly turning error, the compass will read:

$$\begin{aligned} H_c &= \tan^{-1}\left(\frac{\sin(45)\cos(20) - \tan(71.27)\sin(20)}{\cos(45)}\right) \\ &= 26° \end{aligned}$$

As you pass through a magnetic heading of 045°, your compass will be lagging and reading 026°.

Exercise 85

Using the dip angle for Rockcliffe from figure 10.18, the compass heading can be calculated from equation 10.2 for acceleration error:

$$\begin{aligned} \alpha &= \cos(45°)\cos(\tan^{-1}(-0.1)) = 0.7036 \\ \beta &= \tan(71.27°)\sin(\tan^{-1}(-0.1)) = -0.2935 \\ H_c &= \tan^{-1}\left(\frac{\sin(45°)}{0.7036 - 0.2935}\right) \\ &= 59.9° \end{aligned}$$

The compass will be reading 59.9°. Since the aircraft is decelerating, we expect a compass swing to the south and this has, indeed, happened.

Exercise 86

This is the type of problem that sometimes occurs during flight tests but which should never happen in practice. If the heading indicator has been lost in VFR flight then it is no major issue: turn until it feels right, straighten out, allow the compass to stabilise and then make any necessary adjustment. In IFR flight declare an emergency and request non-gyro vectors. However, the exercise as given can be solved easily as follows.

In a rate one turn, an aircraft turns through 360° in 2 minutes (120 seconds). The aircraft therefore turns through 3° every second. To turn through (360 + 80) - 320 = 120 degrees will therefore take 40 seconds.

Chapter 11

Flight Operations

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In Transport Canada's syllabus, *Flight Operations* includes a number of topics that tie together material from other chapters, in particular theory of flight, air law and human factors. There are therefore many references in this chapter to descriptions elsewhere.

Overall, *Flight Operations* covers the considerations of which a pilot needs to be aware to make a safe flight.

11.1 Pilot-In-Command Responsibilities

The responsibilities of the pilot-in-command are many, and include those described in the followingi sections.

11.1.1 Flight Preparation Responsibilities

1. To know the relevant air regulations—see chapter 14.

2. To have up-to-date charts, CFS, etc. See section 6.3 on page 119.

3. To have obtained all of the relevant weather information for the flight—see chapter 5.

4. To have obtained and understood any NOTAMs relevant for the flight—see section 6.4.3 on page 122.

5. To have computed an accurate weight-and-balance—see section 11.6 on page 247.

6. To be current on the aircraft, distinguishing between legal and safe currency. Legally, a VFR pilot who has not flown for 4 years, 11 months can regain currency by completing the open-book, multiple-choice examination issued by Transport Canada. Similarly an IFR pilot may have had no IFR experience for 11 months following a flight test and be legally able to launch into IMC. Realistically, neither of these pilots is likely to be safe, and every pilot should set personal currency standards based on experience and age.

7. To complete an "I'M SAFE" check:

   - Am I suffering from an **illness** that should prevent me flying?
   - Am I taking a **medication** that could affect my flying?
   - Am I under **stress** to the extent that it could affect my flying? See section 1.5.4 on page 15.
   - Have I taken **alcohol** within the last 12 hours or do I still have any effect from alcohol taken earlier? See section 2.2.6 on page 37.
   - Am I suffering from **fatigue?** See section 2.8 on page 42.
   - Have I been **eating** and drinking sensibly and therefore will not be subject to loss of energy or dehydration during the flight? See section 2.2.5 on page 37.

11.1.2 Passenger Responsibilities

8. To provide a safety briefing for the passengers—see section 11.3.1 on page 235.

11.1.3 Aircraft Responsibilities

9. To ensure that the aircraft is airworthy by inspecting the aircraft's documents and performing a thorough walk-around—see *Aircraft Documents* in section 11.1.5 and *Pre-Takeoff Inspection* in section 11.8.5.

10. To be familiar with the numbers and speeds for the aircraft being flown—see section 11.4.5 on page 242.

11. To know the emergency procedures for the aircraft being flown.

12. To use checklists—for information about the design and use of checklists see section 1.8.3 on page 25.

11.1.4 Inflight Responsibilities

13. During flight in VMC, to maintain an effective scan for other aircraft. This involves pausing and focusing the eyes on each piece of sky in a methodical way; it is not possible to detect threats by moving the head continuously backwards and forwards or fixating on one direction. In a small aircraft, passengers should also be asked to point out other aircraft that they spot.

    Transport Canada recommends that pilots turn on their landing lights when flying at low altitudes (below 2,000 ft) and within terminal airspace both by day and night. This increases the chances that the aircraft will be seen, both by other pilots and by birds.

14. To fly at an appropriate altitude for the direction of flight in accordance with the hemispherical rule. For VFR flights above 3,000 ft AGL appropriate altitudes for magnetic (in the southern domestic airspace) or true (in the northern domestic airspace) tracks lying between 000° and 179° are odd thousands plus 500 ft (3500, 5500, 7500, 9500, etc.). For tracks between 180° and 359° appropriate altitudes are even thousands plus 500 ft (4500, 6500, 8500, etc.). For IFR flights the equivalent altitudes are as for VFR with 500 ft subtracted.

15. To obtain clearances for entering class A, B or C airspace.

16. To use correct communications procedures both with ATC—see section 11.3.2—and with other crew members—see section 1.9.1 on page 26.

17. To avoid flying low over herds of reindeer, caribou, moose or muskoxen. Low flight can break up the herds, cause the animals to break limbs, and make isolated animals susceptible to wolf attacks. To

prevent this, pilots must maintain an altitude of at least 2,000 ft above these herds.

18. To be aware of the dangers associated with:

    - thunderstorms—see section 11.3.4 on page 236.
    - hydroplaning—see section 11.3.8 on page 238.
    - slippery runways and be able to interpret the Canadian Runway Friction Index (CRFI) and Runway Condition Code (RWYCC)—see section 11.8.2 on page 251.
    - horizontal and vertical wind shear—see section 11.3.10 on page 251.

11.1.5 Document Responsibilities

Various documents must be carried on board an aircraft in flight. These include:

- The **Journey Log** of the aircraft. Section 605.95 of the CARs states that *"Subject to subsection (2), no person shall conduct a take-off in an aircraft unless the journey log is on board the aircraft."* Subsection (2) allows a takeoff without the journey log if it is not planned that the aircraft will land and shut down anywhere other than the point of departure. The information that must be recorded in the journey log is listed in figure 14.8 on page 328.

- **Certificate of Registration.** Section 202.26 of the CARs states that *"No person shall operate an aircraft in Canada, other than an aircraft referred to in subsection 202.43(1), or a Canadian aircraft outside Canada unless the Certificate of Registration issued in respect of the aircraft is carried on board the aircraft."* The aircraft exempted under 202.43(1) are those with foreign registration.

- **Minimum Equipment List.** If an aircraft is being flown with unserviceable or removed equipment as permitted by the Minimum Equipment List (see section 11.3.3) then a copy of the Minimum Equipment List must be on board the aircraft (as required by section 605.09 of the CARs).

- **Proof of Insurance.** Section 606.02 of the CARs defines the levels of insurance required for various types of aircraft and states, *"Subject to subsection (10), no owner or operator of an aircraft shall operate the aircraft unless there is carried on board the aircraft proof that liability insurance is subscribed for in accordance with this Section."* The subsection referred to relates to hot-air balloons.

- **Personal Licences.** Section 401.03 of the CARs states that *"No person shall act as a flight crew member or exercise the privileges of a flight crew permit, licence or rating or a foreign licence validation certificate unless ... the person is the holder of, and can produce while so acting and while exercising those privileges, the appropriate permit, licence or rating and a valid and appropriate medical certificate."*

- **The Flight Authority.** Section 605.03 of the CARs states that *"No person shall operate an aircraft in flight unless ... the flight authority is carried on board the aircraft."* In this context, "Flight Authority" means the Certificate of Airworthiness or Flight Permit.

- **The Aircraft Flight Manual** (AFM) for the aircraft type. Section 605.04 of the CARs states that *"No person shall conduct a take-off in an aircraft for which an aircraft flight manual is required by the applicable standards of airworthiness, unless the aircraft flight manual ... is available to the flight crew members at their duty stations."*

  The AFM (sometimes loosely known as the Pilot's Operating Handbook, POH) is a book containing the information and instructions required to operate the aircraft safely. The pilot must comply with this. A typical AFM contains the following:

  - **Limitations**—the "envelope" of maximum speeds, maximum weights, allowable centre of gravity range, maximum engine RPM, temperatures and oil pressures, etc. for the engines, allowable manoeuvres and other limits within which the aircraft must be operated.
  - **Operating procedures**—aircraft procedures, speeds and configurations used to:
    * achieve expected performance and behaviour in normal situations.
    * achieve safe outcomes in some specified abnormal or emergency situations (such as a forced landing after engine failure).
  - **Performance**—the required variation of the aircraft's maximum allowable weights, as affected by air pressure and temperature, in order to:
    * takeoff or land in available runway distance.
    * climb at the minimum required gradient, or greater gradient needed to clear obstacles in the intended flight path following takeoff or missed approach.
  - **Other information and instructions** necessary to operate the aircraft safely.

- **Weight and Balance Report.** In accordance with section 605.92 of the CARs, each aircraft must have its empty weight and position of its empty centre of gravity recorded. If a modification or a major repair is made to an aircraft involving a change in the empty weight or centre of gravity, the person who made the change must make an entry in the journey log as soon as practicable after the change but, at the latest, before the next flight. Where an aircraft can be operated in two or more different configurations, a separate weight and balance report addendum is required for each. The Weight and Balance information must be available to a pilot before each flight and this is normally achieved by having a copy of the weight and balance report on board the aircraft or the relevant information copied into the journey log. Large aircraft have to be physically reweighed every five years (see Standard 625 Appendix C of the CARs) but there is no requirement that small aircraft ever be reweighed.

Anecdote 35 *I once bought an aircraft where the owner found, when putting the papers together for the transfer, that he had lost the original weight and balance certificate. However, he had the relevant numbers recorded in the journey log. Before I took delivery, I insisted that the aircraft be weighed and that a new weight and balance certificate be issued. This found that the aircraft was actually some 50 pounds-force heavier than the figures the previous owner had been using. This illustrates the danger of the "weigh it once and then adjust each time equipment is added or removed" approach. The aircraft was 35 years old and had accumulated a large number of small incremental items over the years.*

There is also some evidence that the **Interception Orders** need to be carried on board. Section 602.144 of the CARs states that *"The pilot-in-command of an intercepting aircraft and the pilot-in-command of an intercepted aircraft shall comply with the rules of interception set out in the CFS."* As interceptions occur infrequently, possibly the best way to assure compliance with this is to have the interception orders available from the pilot's seat (normally by having the CFS at hand).

There are also certain documents that must *not* be carried on board an aircraft. These include the technical logs: see section 14.6.16 on page 327.

11.1.6 Monitoring Radio Interference

Most pieces of electronic equipment, and in particular computers, have internal oscillators generating very regular pulses for timing and clocking purposes. These oscillators radiate electromagnetic waves at various frequencies and these waves can interfere with other electronic equipment in the neighbourhood. The engineering discipline involved with ensuring that pieces of equipment do not interfere with each other in this way is known as *Electromagnetic Compatibility* (EMC). EMC engineering aims to reduce the amount of radiation emitted from a device while reducing its susceptibility to incoming radiation.

Increasingly, both passengers and pilots are bringing electronic equipment onto aircraft, including cellular telephones, portable computers and entertainment devices, and there is the potential for interference with navigation and other aircraft systems. Transport Canada issued an *Air Carrier Advisory Circular* (ACAC) on the subject in 1996, requesting reports about incidents of interference. By the middle of 2001 no instance of interference had been reported and Transport Canada issued a *Commercial and Business Aviation Advisory Circular* reporting anecdotal evidence and repeating the request for reports.

Within the USA, the FCC has carried out extensive testing and concluded that the switching on or use of hand-held electronic calculators can cause interference to ADF equipment in the 200-450 kHz frequency range when the calculator is within 5 ft of the loop or sense antennæ, or lead-in cable installation of the system.

In summary, the area of electromagnetic compatibility issues on aircraft appears to be a theoretical possibility supported by little hard evidence. Transport Canada has issued guidelines saying that "the onus for determining if passenger-operating electronic devices will cause interference is placed on the operator of the aircraft because there are no airworthiness standards for the manufacture of passenger-operated devices, no maintenance standards and no performance standards in relation to their use on an aircraft".[1]

[1] Given the complexity of EMC engineering, it is surprising that the responsibility for carrying it out should be placed on those running an aircraft business. Guidelines appear to miss the complex system of testing and accompanying labelling that is carried out on domestic electronic equipment (e.g., CAN/CSA-C108 in Canada, 89/336/EC in the European Union). A relatively simple solution would be to ban portable devices not marked as being in accordance with the requirements of these specifications. This would not be a complete solution but it could offer some protection.

11.2 Aerodrome Operations

Much of the material required for this topic is included in the AGA (Aerodromes) section of the Aeronautical Information Manual (AIM).

11.2.1 Aerodrome Types

Any piece of land or water used for the arrival, departure, maintenance or movement of aircraft is an *aerodrome*.

Section 301 of the CARs—see section 14.6.15 on page 326—outlines the procedure that an aerodrome operator needs to carry out in order for the aerodrome to be *registered*. Registered aerodromes have a CFS entry.

Aerodromes located in built-up areas of a city or town, providing a main operations base for an air carrier or having a scheduled passenger-carrying service are required to fulfil a further process, known as *certification*. Such certified aerodromes are then also known as *Airports*.

11.2.2 Runway Numbering

Runways are numbered in accordance with their orientation either to the north pole or the north magnetic pole. In the southern domestic airspace the orientation is specified as a magnetic bearing, whereas in the northern domestic airspace it is a true bearing. The runway number is the most significant two digits of the bearing, rounded where appropriate, and is painted on the approach end of the runway, suffixed by the letter T if the bearing is true. In Canada, although not in the USA, bearings less than 100 are prefixed with a zero; for example, a runway in the southern domestic airspace with a magnetic bearing of 36° is marked as runway 04 (040 being the closest multiple of ten to 36) in Canada or runway 4 in the USA.

Where an airport has two or more parallel runways, they are designated by the same number but with the letter L, C or R suffixed to indicate left, centre or right.[2]

The magnetic variation of airports changes over time as the magnetic north pole moves, and consequently runway numbers change.

Anecdote 36 *In 2005 Halifax's runway 06/24 was renumbered as 05/23 while I was in the air flying towards it and I was cleared to land on a runway that I didn't know existed—a good reason for checking NOTAMs more carefully than I had.*

[2]There is a point of interest for Santa Claus here. Both ends of a runway situated exactly at the north pole would be labelled 36T but neither end is L, C or R of the other.

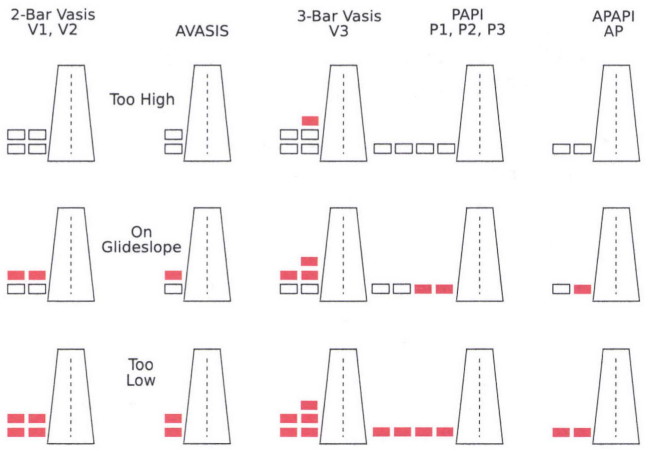

Figure 11.1: VASIS and PAPI

11.2.3 VASIS/PAPI

Both the *Visual Approach Slope Indicator System* (VASIS) and the *Precision Approach Path Indicator* (PAPI) are sets of lights installed on the left-hand side of a runway to provide landing pilots with an indication of whether they are above or below a glidepath that assures obstacle clearance. The glidepath angle is normally 3° and obstruction clearance is provided as far as 4 nm from the threshold, within 6° either side of the runway centreline.

Figure 11.1 illustrates the VASIS and PAPI deployed at various civilian airports in Canada. In general, whatever the system, a preponderance of white lights indicates that the aircraft is above the optimal glideslope and a preponderance of red lights that it is below.

Of course, in different types of aircraft the pilot is situated at a different height above the wheels. The vertical distance between the lowest part of the aircraft in landing configuration and the pilot's eyes is known as the Eye-To-Wheel Height or EWH. The EWH can be as much as 14 metres for an aircraft such as a Boeing 747. The importance of being aware of the EWH of the aircraft, and the type of PAPI with which the runway is equipped, is shown by the incident on 11th November 2007 at Fox Harbour, N.S., when a Bombardier Global 5000 (EWH of 5.2 metres) landed 2 metres before the threshold of runway 33, causing substantial damage to the aircraft and injuries to passengers. The crew had flown into Fox Harbour many times in a Challenger CL604 which has an EWH of 3.7 metres. The APAPI installed for runway 33 is suitable only for aircraft with EWH of up to 3 metres.

Details of the precise form of VASIS or PAPI at a particular airport are to be found in the CFS and Canada Air Pilot (CAP) entries for an airport:

- Within the CFS, VASIS is indicated on the airport

diagram by a circled V at the runway threshold. PAPI is indicated by a circled P. The type of VASIS or PAPI is then given in the *LIGHTING* section.

- In the Canada Air Pilot, the precise type of VASIS or PAPI (e.g., V1) is indicated in the runway plan view by a circle at the runway threshold.

Figure 11.2 lists the suitability of different types of PAPI and VASIS for different values of EWH.

Type	For EWH up to ...	Notes
VASIS V1	3 metres	
VASIS V2	7.5 metres	
VASIS V3	14 metres	Aircraft with EWH greater than 7.5 metres use the furthest and middle bars; other aircraft use the middle and closest bars
VASIS AV	3 metres	
PAPI P1	3 metres	
PAPI P2	7.5 metres	
PAPI P3	14 metres	
PAPI AP	3 metres	

Figure 11.2: Types of PAPI and VASIS

11.2.4 Aerodrome Lighting

Approach, runway and aerodrome lighting varies from airport to airport and the CFS and the General Pages of the Canada Air Pilot have descriptions of the various types. In the CFS the diagrams are contained in the general pages in section A.

Exercise 87 *The* LIGHTING *entry in the CFS for a particular airport contains the following:*
`09-AJ AS(TE ME)V1, 27-AS(TE ME)V1.`
What does this tell you about the runway lighting and slope indication systems?

Answers to exercises in this chapter can be found in section 11.10 starting on page 257.

11.2.5 Obstruction Marking

Standard 621.19 of the CARs, entitled *Standards Obstruction Markings*, deals with the complex area of obstruction marking. The following types of obstruction must be marked and lit in accordance with the standard:

- Any obstacle penetrating an airport obstacle limitation surface. This is a complex surface defined for each airport that takes into account the arrival and departure paths of aircraft.
- Any obstruction greater than 90 metres AGL within two nautical miles of the centreline of a recognised VFR route (e.g., valley, railway, river or highway).
- Any permanent free-hanging wire where any portion of the wire or supports is more than 90 metres from the ground.
- Any obstruction taller than 150 metres.
- Any other obstruction that is assessed as being a possible hazard for aircraft.

11.2.6 Windsocks

Windsocks are officially known as *Wind Direction Indicators*. The positions of the windsocks on an aerodrome are given in the plan view of the aerodrome in the CFS. For runways longer than 4,000 ft, two windsocks are required, each 500 ft from the threshold and typically on the left-hand side during approach. Generally, runways shorter than 4,000 ft have a single windsock, normally positioned near the centre.

At airports (i.e., certified aerodromes) standard windsocks must be used and, at night, illuminated. When dry, the angle of such a windsock in different wind conditions is listed in figure 11.3. The angles of wet windsocks are not defined.

Wind Speed	Windsock Angle
15 knots or above	Effectively horizontal
10 knots	5° below the horizontal
6 knots	30° below the horizontal

Figure 11.3: Angles of a Standard Windsock

At aerodromes that are not certified (i.e., are not airports), the windsocks may be non-standard. A few airports in Canada still have *Signal Squares* to indicate wind direction, runway in use, direction of the circuit and other aerodrome information. The size, layout and content of the Signal Square is defined in ICAO Annexe 14[3] where a distinction is made between a wind direction indicator (windsock) and a landing direction indicator.

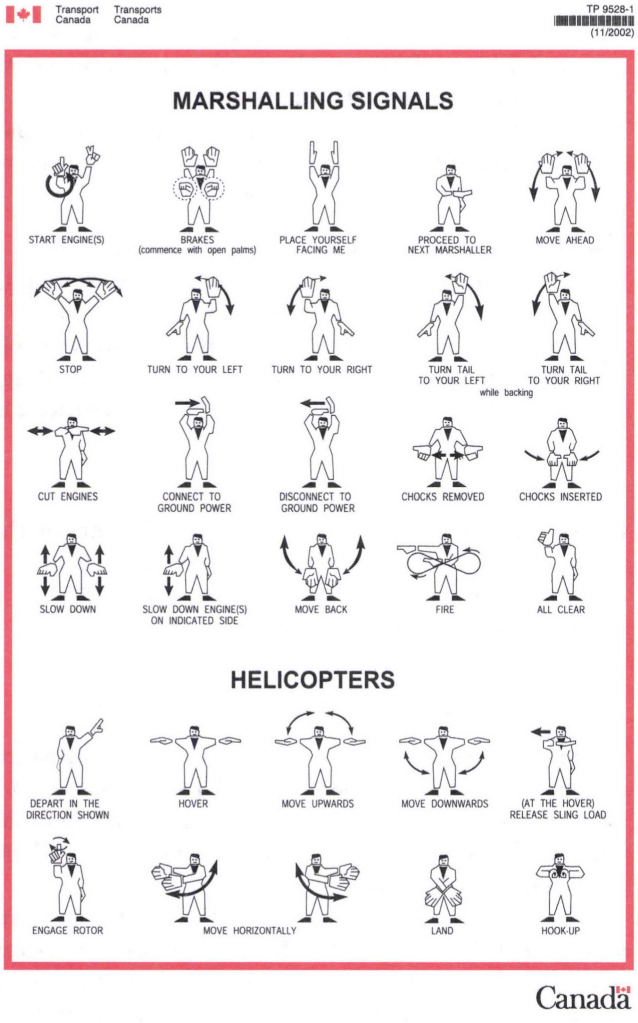

Figure 11.4: Marshalling Signals (Transport Canada)

11.2.7 Marshalling Signals

When an aircraft is taxiing at an aerodrome there is a standard set of marshalling signals that can be used—see figure 11.4 which is taken, with permission, from Transport Canada's publication TP9528.

11.3 Aircraft Operation

11.3.1 Passenger Briefings

The pilot-in-command is responsible for ensuring that passengers are briefed before the engines are started and again before landing. In summary, the briefing must include at least the following:

- the location and operation of all normal and emergency doors and windows.
- the location and operation of doors in cargo compartment(s) that can be opened from inside.
- how to bring seat backs into the upright position.
- the operation of seat belts and shoulder harnesses.
- the location and operation of fire extinguishers.
- the location of first aid kits and survival gear.
- the positions where baggage may be safely stowed.
- the policy related to the use of portable electronic devices on the aircraft.
- any prohibition related to smoking.
- where the aircraft is unpressurised and it is possible that the flight will require the use of oxygen by the passengers, the location and means of operation of oxygen equipment.
- where the aircraft is pressurised and is to be operated at an altitude above FL250, the location and means of operation of oxygen equipment.
- in the case of an over-water flight where the carriage of life preservers, individual flotation devices or personal flotation devices is required, the location of those items and how to use them.
- the location and operation of the emergency locator transmitter (ELT).

In a light aircraft, other aircraft-specific briefings will probably be needed. For example, if a front seat passenger is in a position to touch dual controls then he or she should be warned not to touch them without permission, emphasising that, rather than the controls, the shoulder harness or door strap should be gripped during rotation and flaring. Other examples of briefings in light aircraft might include asking the passenger to point out any aircraft seen outside and asking the passenger not to talk during the approach and landing (creating a "sterile cockpit").

11.3.2 Radio Communications

The basic concepts of radio transmissions are described in section 7.2 on page 130.

Most air-to-ground radio communication uses Very High Frequency (VHF) signals with frequencies between 118 and 137 MHz. In the north of Canada and in the North Atlantic, High Frequency (HF) radios are used in the 2.8 to 22 MHz band.

[3] Available from `https://www.caa.govt.nz/ICAO/Annex_14_Vol_I_Amdt_11_EFOD.pdf`

In order to operate an aircraft radio, a pilot needs to hold a *Restricted Operator Certificate* with Aeronautical Qualification issued by Innovation, Science & Economic Development (ISED) Canada.

Sections 602.133, 602.134 and 602.135 of the CARs specify how French and English may be used on the radio in Canada. In summary:

- All air traffic control units and flight service stations provide services in English.
- Terminal control units in Bagotville, Montréal, Ottawa and Québec also provide services in French.

Pilots need to be familiar with the correct terminology to use on the radio. As the same frequency is shared by controllers and pilots for both transmitting and receiving, pilots should keep transmissions short, succinct and standard:

- Forget phrases such as "with you" when checking in with a new controller: "Montréal Centre, Foxtrot Alpha Bravo Charlie, three thousand five hundred feet" is sufficient and passes all of the required information.
- Do not use the term "active" at an uncontrolled airport in phrases like "Alpha Bravo Charlie is clear of the active". Using the runway number conveys useful information to an incoming pilot without needing more air time: "Alpha Bravo Charlie clear of two seven". It could also save the incoming pilot from having to make a radio call to determine which runway is active.
- Do not make unnecessary position reports on 126.7 MHz. In some areas, this frequency is almost perpetually clogged with reports of the form "Traffic on 126.7. Alpha Bravo Charlie is over a lake that you have never heard of at 3,000 ft heading towards a town that you have never heard of. Conflicting traffic, please advise."
- Remember the availability of 122.75 MHz (in the Southern Domestic Airspace) and 123.45 MHz (Northern Domestic Airspace) for pilot-to-pilot communications. If you are flying with other pilots this is the frequency to use to exchange positions and intentions.
- If you are landing IFR at an uncontrolled airport, do not assume that any VFR pilots who happen to be in the circuit are familiar with IFR waypoints or approach procedures. "Alpha Bravo Charlie is over GIZMO descending to the MDA for the circling approach for two seven" may convey no information at all to a VFR pilot on frequency.
- Be sure you understand common terminology such as *Roger* ("I have understood your transmission") and *Wilco* ("I have understood your transmission and will comply with the instruction"). Do not misuse these terms: for example it makes no sense to respond to "Papa Tango November, confirm you are a Cessna 172" with "Roger".
- If you are flying VFR, avoid reading back all instructions and clearances. Readbacks are required for IFR flight but a simple "Wilco" is normally sufficient from VFR pilots: "Papa Tango November, turn left twenty degrees for spacing" "Papa Tango November, Wilco". A readback *is* required for all hold short instructions.

Possibly the best way to determine the correct terminology is to read articles by controllers about their pet hates from pilots: *IFR: the Magazine for the Accomplished Pilot* is particularly good (and often harsh) at this kind of criticism.

11.3.3 Minimum Equipment List

Minimum Equipment Lists (MELs) provide a measure of control of defects in an aircraft. MELs are lists of systems and equipment installed in an aircraft annotated with the level of defects and the time period for which they may be tolerated.

The content and structure of MELs is laid down in section 605.07 of the CARs. Irrespective of the existence of a MEL for a particular aircraft, it is the responsibility of the pilot-in-command to ensure that the aircraft does not take off if he or she believes that aviation safety is affected by unserviceable or removed equipment.

If something on a MEL conflicts with an airworthiness directive, the airworthiness directive takes precedence.

If no MEL is extant for a particular aircraft, then the lists given in the CARs (extracted in figure 14.6 on page 325) apply for day VFR, night VFR and VFR Over-the-Top flights.

11.3.4 Thunderstorm Avoidance

For details of the mechanisms by which thunderstorms form and dissipate, see section 4.15 on page 89.

It is well known that flying close to a thunderstorm can potentially destroy almost any aircraft: the combination of turbulence, lightning strikes and water ingestion into the engine can easily cause fatal accidents. Pilots are therefore advised to avoid thunderstorms by at least 20 nautical miles, although severe turbulence can be felt up to 50 nautical miles from supercell thunderstorms.

In VMC, the cumulonimbus clouds that mark thunderstorms can normally be seen at great distances, particularly if the aircraft is flown above any low-level broken or scattered clouds, and in these circumstances avoidance is relatively easy if the thunderstorms are isolated *pulse thunderstorms*—thunderstorms in an area where the wind shear is weak and the downdraft falls close to the updraft, cutting off the inflow of air. The downdraft also reduces the momentum within the updraft.

In IMC this is not so easy and, for this reason, it is best to fly VFR rather than IFR when thunderstorms are likely. However, an IFR pilot has two options: to detect lightning (which always accompanies a thunderstorm) or to detect heavy rain (which normally does).

- **Lighting strikes** can be displayed in the cockpit from ground-based lightning detection systems (e.g., ADS-B) or by a sferics device (e.g., Strikefinder or Stormscope) mounted in the aircraft. In either case, the display can be presented on a dedicated instrument or as an overlay on a GPS moving map. Figure 10.33 on page 224 illustrates a sferics display.

  Both of these systems suffer from disadvantages. The ground-based systems are not generally available across Canada (although signals can be received along the USA border), and the information is not always up-to-date when storms cells are building quickly. The aircraft-mounted systems require fairly sophisticated interpretation.

  With either a receiver for ground-based observations or a sferics device in the aircraft there are certain patterns to watch for. For example, a cell "breaking off" from the line of cells of which it is a part and (in the Northern hemisphere) turning right indicates a severe thunderstorm, possibly generating a tornado.

- **Heavy Rain** can be detected by radar. Again a pilot may use a device in the aircraft receiving information from ground-based radar or (in larger aircraft) may have a radar mounted in the aircraft itself. In the absence of these, a pilot may appeal to a ground controller for information being displayed on primary radar. This can be useful for detecting intense storms but the primary radar is not designed to identify weather patterns, the number of locations with primary radar is decreasing and the information cannot be relied on totally.

Sferics devices and radar are described in more detail in chapter 10.

If it is not possible to avoid a thunderstorm then the following may increase your chances of survival:

- Fly as far upwind of the thunderstorm as possible.
- Tighten seat belts and shoulder harnesses and ensure that all luggage is securely tied down.
- Avoid icing if possible by penetrating below the icing level or above the area where the temperature is below −20°C (where the air is probably too cold to produce icing). Of course, with the violent updrafts and downdrafts in a thunderstorm moving air about, it may be very difficult to define the icing level.
- Turn pitot, carburetor or jet inlet heat on as appropriate.
- Reduce speed to turbulence penetration airspeed (V_a).
- Turn cockpit lights onto maximum intensity to cause the pupils of the eyes to close, reducing the chance of blindness caused by flashes of lightning.
- Disengage the altitude hold and speed hold modes on the autopilot.

If you do enter a thunderstorm, remember that the quickest way out will probably be by going straight through—avoid a turn in these conditions if possible.

11.3.5 Mountain Flying Operations

Flying in mountainous areas presents particular hazards including:

- **Reduced Pressure.** Winds passing through valleys are subject to the Bernoulli Principle: they speed up and the local pressure drops. This causes altimeters to over-read (i.e., they indicate altitudes that are higher than the correct value).
- **Mountain Waves.** Winds blowing over a mountain range at a critical speed will often create standing waves with wavelengths of about 8 to 10 miles downwind of the mountains. These waves can be identified by the presence of lenticular clouds: lens-shaped clouds that do not move downwind; see section 4.11.3 on page 82. Glider pilots can use these waves to ascend to altitudes of 30,000 ft or more, but for power aircraft they can represent areas of severe turbulence.
- **Downdrafts and Turbulence.** As wind flows over a mountain range it descends on the lee side causing downdrafts. In extreme cases an aircraft may not be able to out-climb these downdrafts. This area in the lee of the mountain is also likely to exhibit a low pressure, causing the altimeter to

over-read. Because of this, a pilot in one of these downdrafts may not realise that the aircraft is actually descending.

Anecdote 37 *While flying IFR over Millinocket in Maine, USA, close to Mt Katahdin (5,268 ft ASL) my wife and I once met a combination of these effects: the winds speeding up through the mountain passes exceeded 100 knots and our Cessna 172 was, for a while, actually flying backwards over the ground. The turbulence meant that we couldn't hold altitude and, as we were flying IFR, we requested and were given a block altitude to allow us to deviate up to 1,000 ft from our assigned altitude. Luckily we had broken out of cloud and were able to see our position relative to the mountains and take corrective action.*

In addition to being aware of these hazards, there are other guidelines to be followed when mountain flying:

- Always remain in a position where you can turn toward lowering terrain.
- When flying towards upslope terrain always remain in a position where, if you reduce the throttle to idle, you can lower the nose for a normal glide and perform a 180-degree turn without hitting the ground.
- Consider the density altitude carefully. A high density altitude will affect not only takeoff distance required but also the ability of the aircraft to out-climb rising terrain.
- If you are flying VFR, be aware of the flight visibility both ahead of *and behind* you. Do not continue a flight into deteriorating visibility.
- If you are flying IFR, request a block altitude early to give yourself room for rapid altitude changes.
- Control altitude changes (caused by mountain wave) with power and trim rather than pitch.
- Make sure you have a clean windscreen and use vertical rather than horizontal cleaning strokes to avoid masking horizontal cables strung across valleys when operating at low level in poor visibility.

11.3.6 Wildlife Hazards

The first reported bird strike occurred on 7th September 1905 when Orville Wright hit a bird (probably a red-winged blackbird) as he flew over a cornfield near Dayton, Ohio, USA. The first reported mammal strike occurred on 25th July 1909 at the start of Louis Blériot's first flight across the English Channel from Les Baraques, France. During engine warm-up of his Bleriot XI, a farm dog ran into the propeller.

Wildlife continues to represent a hazard at airports and the Federal Aviation Administration (FAA) in the USA has issued a document entitled *Wildlife Hazard Management at Airports: A Manual for Airport Personnel.*[4]

Birds, of course, are a major hazard to aircraft arriving at or departing from an airport but, in addition, in North America, deer, moose, coyotes and even alligators have wandered onto runways and caused serious problems for departing and landing aircraft. Aircraft collisions with wildlife annually cost the civil aviation industry in the USA about $500 million in direct damage and associated costs, and over 500,000 hours of aircraft down time.

The RAC section of the AIM contains maps of the migratory routes of many birds. Pilots should study these to anticipate the types of bird that may be met during a flight. Swans, for example, migrate during the Spring and Autumn at altitudes up to 12,000 ft.

Transport Canada requests that pilots who experience a bird strike report the incident by completing a *Bird/Wildlife Strike Report* form, copies of which can be obtained from any Flight Service Station. Alternatively the strike can be reported online at `http://www.tc.gc.ca/aviation/wildlife.htm` or on the telephone at 1-888-282-BIRD.

11.3.7 Wheelbarrowing

Wheelbarrowing occurs in a tricycle gear aircraft when the nose-wheel rather than the main gear is forced to support an abnormal share of the aircraft's weight. The main wheels may be lightly loaded or even clear of the runway. Wheelbarrowing may be caused by touching down on the nose-wheel, excessive braking or friction between the wheels and runway caused by a side-skid. Wheelbarrowing can damage a nose-wheel or cause an aircraft to yaw uncontrollably off its intended course, particularly if there is a crosswind.

11.3.8 Hydroplaning

Hydroplaning is hazardous because it creates a loss of control as the tire skims on a wet runway. There are several types of hydroplaning:

Dynamic Hydroplaning. This occurs when the tire is lifted completely above the surface of the runway.

[4] Available from `https://www.faa.gov/airports/airport_safety/wildlife/resources/media/2005_FAA_Manual_complete.pdf`

As little as 3mm of water combined with the "critical speed" of the tire can cause this.

Viscous Hydroplaning. This can occur at slower speeds where, rather than the water lifting the tire from the runway, the tire slips on a thin film. This only occurs on smooth runways.

Reverted Rubber (Steam) Hydroplaning. If an emergency occurs during takeoff or landing the pilot often locks the brakes. On a wet runway, the tire track can heat up if friction causes some of the rubber to revert to a gummy state, trapping water. The water turns to steam and steam pressure lifts the tire from the runway.

The critical speed (in knots) above which hydroplaning can occur for a rotating tire inflated to a pressure of P pounds per square inch is given by: $9 \times \sqrt{P}$. For locked wheels, the critical speed reduces to $7.7 \times \sqrt{P}$. Keep this information in mind while driving to the airport; this formula will work for your car, too!

Hydroplaning can occur at any speed above this value if there is 3mm or more of water on the runway.

Exercise 88 *An aircraft's main tires are inflated to 25 lb/square inch. At what speeds is hydroplaning possible on a wet runway if the wheel is rotating?*

When landing on a runway where hydroplaning is a possibility:

- approach to land at the slowest safe airspeed.
- land firmly.
- lower the nose wheel as soon as the main wheels are firmly down.
- know the critical speed and avoid heavy braking above this speed.
- retract the flaps immediately after landing to place more weight on the wheels.
- divert to an alternate airport if conditions indicate that hydroplaning might happen on runways with a strong crosswind.

Many accidents have been attributed to hydroplaning. One example occurred at Hamilton, Ontario on 15th November 2005 when a Gulfstream 100 was landing on runway 12 at night in IMC. At 400 ft to 500 ft AGL the crew saw the runway and the aircraft touched down on the wet runway with about 3,000 ft remaining. The flight crew used all available braking systems to slow the aircraft but it ran off the end of the runway and travelled 122 ft down a slope before coming to an abrupt stop when the nose wheel sheared off. The Transportation Safety Board (TSB) report states:

> *Although the available 3,000 ft of runway remaining exceeded the unfactored estimated ground roll of 2,200 ft, the aircraft was unable to stop. A touchdown speed higher than the landing reference speed (Vref), slow deployment of the thrust reversers, standing water at the intersection of the runways, friction values at the runway ends that were at or below the Transport Canada runway maintenance planning level, and limited tire tread depth likely contributed to the runway excursion. During the landing roll, the aircraft's tires hydroplaned, reducing the braking forces.*

11.3.9 Taxiing

After landing, unless instructed otherwise by a controller, you are expected to continue in the landing direction on the runway to the next taxiway and exit at that point, rolling until all parts of the aircraft are past the holding lines. Without instruction from a controller, a pilot should *never* exit a runway onto a cross-runway rather than a taxiway.

When taxiing, you must read back all hold short instructions issued by a controller; this is one of the few instructions that VFR pilots are obliged to read back.

Anecdote 38 *As with any instructions from a controller, be aware that even reading back the clearance doesn't ensure that it is lodged in one's brain. I was once leaving a fly-in at Oshawa airport and was taxiing in a long line of departing aircraft. Runway 30 was in use and the ground controller was repeating the instruction "Taxi Bravo, hold short of 30" to each aircraft. To me he said "Taxi Bravo, hold short of 22" and I read it back correctly while hearing and understanding "hold short of 30". Luckily my wife felt uncomfortable with the clearance before I reached runway 22 and insisted I ask for clarification.*

11.3.10 Effects of Wind Shear

Wind shear is a sudden difference in wind speed or direction either vertically or horizontally. It is commonly observed near:

- **Weather fronts.** When the temperature difference across the front is 5°C or more and the front moves at 15 kt or faster, significant wind shear can occur both horizontally and vertically.

- **Low Level Jets.** When a low-level jet forms above the boundary layer ahead of a cold front, significant low level vertical wind shear can develop near the lower portion of the jet.
- **Mountains.** When winds blow over a mountain, vertical shear occurs on the lee side. If the flow is strong enough, rotors may form, which are dangerous to ascending and descending aircraft.
- **Inversions.** On a clear night a radiation inversion may form and the wind below the inversion is affected by ground friction whereas the wind above the inversion is not. The change in wind can be 90° in direction and 40 kt in speed.
- **Microbursts and Downbursts.** When an outflow boundary moves away from a thunderstorm due to a shallow layer of rain-cooled air spreading out at ground level, both speed and directional wind shear can result at the leading edge of the three dimensional boundary. These microbursts are typically about 1 nm in diameter at 2,000 ft AGL, spreading to about 2-3 nm at the surface. Within the microburst, vertical winds (upwards and downwards) of up to 6,000 ft per minute have been observed. The effect of a microburst on an aircraft is illustrated in figure 11.5: the aircraft in that figure is taking off and experiencing a headwind, a downdraft and a tailwind in quick succession.

The meteorological phenomena listed above are described in the more detail in section 11.3.10 on page 239.

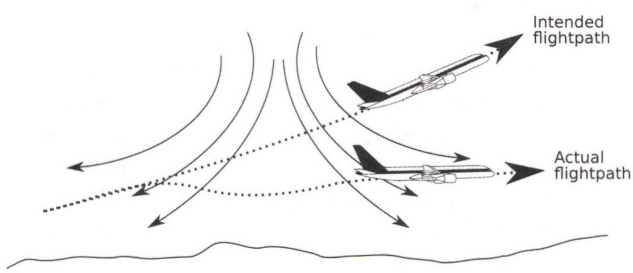

Figure 11.5: Trying to Climb Through Wind Shear

The first indications that a pilot may have of wind shear are:

- a warning from a ground controller originating from information from a Doppler weather radar—see page 250
- observation of blowing dust, rings of dust, dust devils (i.e., whirlwinds containing dust or sand) and any other evidence of strong local air outflow near the surface
- a sudden change in airspeed, often more than 15 knots
- a sudden change in ground speed
- a sudden change in pitch, often of more than 5°
- a sudden change in heading, often of more than 10°

If wind shear is encountered, the only available actions for a pilot may be to apply full power and pitch up to the maximum angle of attack to try to outclimb the downdraft.

Numerous fatal aircraft accidents including USAir flight 1019 on 2nd July 1994 at Charlotte/Douglas Airport and Delta Airlines flight 191 on 2nd August 1985 at Dallas/Fort Worth International Airport have been attributed to wind shear. If you encounter wind shear of any type, it is essential that you report it to ATC as soon as possible.

11.3.11 Slipping

A slip is an aerodynamic condition where the aircraft is moving simultaneously sideways and forward, relative to the oncoming airflow—the aircraft's nose is not pointing directly into the relative wind. Flying in a slip is aerodynamically inefficient and can cause motion sickness (and even fear!) in passengers—in a light aircraft it may be worth briefing passengers before slipping.

There are two basic forms of slip, both of which are aerodynamically identical once established. The distinction depends on whether the aircraft's heading is the same as its track across the ground:

1. In a *side-slip* the aircraft's heading and ground track are the same.
2. In a *forward-slip* the aircraft's track differs from its heading.

In either type of slip, the aircraft is flying in an aerodynamically inefficient manner and will lose height unless power is added to compensate for the additional drag. Height is lost more rapidly in a forward-slip.

During a crosswind landing, both types of slip may be used. If the aircraft is too high on final approach, a forward slip without the compensating additional power may be used to lose height. In this case the lower wing would be pointing into the wind. Once the extra height has been lost, the pilot can transition into a side-slip for the actual landing by allowing the aircraft's nose to turn to align with the runway centre line. The aircraft's track and heading are then both aligned with the runway centre line for landing. Power would typically be added during the side-slip to slow the rate of descent. During

the descent to the runway, the pilot should anticipate that the crosswind will back (see section 4.6.1 on page 65 for a description of the term "back") and reduce in strength and compensate for this with the bank angle of the slip.

In cruise, if you see another aircraft approaching at your altitude, the quickest way of avoiding a collision may be to descend rapidly, using a forward-slip to maximise the rate of descent.

11.4 Aircraft Performance

There are numerous books about aircraft performance. For pilots of light aircraft, one excellent book is *Piloting for Maximum Performance* by Lewis Bjork.[5] As well as clearly explaining the various concepts, Bjork also suggests useful performance-related flying skills that should be practised and describes experiments to perform in your own aircraft to determine specific performance values—confirming the values in the POH and determining ones normally not given in the POH.

11.4.1 Lift/Drag Ratio

The Transport Canada syllabus includes discussion of the Lift/Drag ratio under Flight Operations. In this book it is included in section 9.5.6 on page 185 under Theory of Flight.

11.4.2 Effects of Density Altitude

The concept of Density Altitude is also discussed in section 12.4.8 on page 272 when considering its effect on engine power.

An aircraft generates lift by deflecting the air passing over its wings downwards. Clearly the density of the air will affect the amount of lift created. When calculating the effect of different conditions, rather than use the actual density of the air (in kg per cubic metre), pilots use the concept of pressure and density altitudes.

Consider an airport such as Regina International. The actual elevation of this airport is 1,894 ft ASL. If the current atmospheric pressure is low then, to an aircraft rolling down the runway, it appears to be equivalent to an airport at a higher altitude on a standard pressure day. The height of the equivalent airport is known as the *Pressure Altitude* of Regina. Pressure altitude is best calculated for flight planning by using an aviation calculator, but if one of these isn't available then an estimate can be made by assuming that each inch of mercury different from the standard 29.92″ is equivalent to about 1,000 ft. If you are at an airport and an aircraft is available then the current pressure altitude can be found easily by setting the altimeter to 29.92″ Hg and reading the altitude displayed.

Exercise 89 *Houston, BC, lies at 2,150 ft above sea level, and the current altimeter setting is* 29.34″ *Hg. What is the current pressure altitude of Houston?*

In addition to the pressure being different from standard, it is also possible that the temperature and humidity are different from standard. These also affect the density of the air and therefore the takeoff distance of aircraft and the power produced from a normally-aspirated engine. A hot, moist, low pressure day results in the longest takeoff runs and a cold, dry, high pressure day results in the shortest. When pressure, humidity and temperature are taken into account, the height of an equivalent airport on a standard day is known as its *Density Altitude*. The only practical way of calculating density altitude is to use an aviation calculator, although many of these are inaccurate because they do not take humidity into account.

Exercise 90 *Houston, BC, lies at 2,150 ft above sea level, the current altimeter setting is 29.34″ Hg, the temperature is* 25° *C and the dew point* 0° *C. What is the current density altitude of Houston?*

Density altitude has a significant effect on the takeoff distance and climb performance of an aircraft, affecting both the amount of lift generated by the wings and the efficiency of a conventionally aspirated engine. Its effect on descent profiles and landing distances is much less, as engine power and thrust are not significant when landing. Landing distances will be slightly longer in high density-altitude conditions because the true airspeed on approach will be higher. For example, this difference can be seen by comparing the takeoff and landing distance rolls for a Cessna 172M at the same pressure altitude but at different temperatures. According to the handbook, between 0°C and 40°C the takeoff roll increases by 33% but the landing roll only by 14%.

11.4.3 Attitude Plus Power Equals Performance

As described in section 9.5 on page 178, the behaviour of an aircraft in flight depends on the relative magnitudes of the thrust (from the engines), the lift (from the wings), the drag (from the lift and aerodynamic behaviour of the aircraft moving through the air) and

[5] ISBN 978-0070056992

the weight. Each of these is a force and the pilot has some control over each:

- the thrust can be altered by changing the power output of the engine.
- the lift can be altered by changing the angle of attack of the wings (the "attitude" of the aircraft).
- the drag can be altered by changing the angle of attack of the wings and by modifying aerodynamic drag by raising or lowering landing gear, flaps, spoilers, etc.
- the weight can be changed *in extremis* by throwing baggage overboard.

By balancing these forces, the pilot controls the performance of the aircraft.

11.4.4 Ground Effect

Ground Effect is described in section 9.5.5 on page 184.

11.4.5 V Speeds

A number of particular airspeeds associated with an aircraft are expressed in terms of "V-speeds", represented by the letter V with various suffixes. Generally, V-speeds change for different loaded weights but are given in pilot operating handbooks as a single number that needs to be adjusted, if necessary, to account for the actual weight of the aircraft. The V-speeds include the following.

Best Angle of Climb (V_x)**.** This speed is the one at which the aircraft will reach a particular altitude with the least forward distance across the ground—the speed at which an aircraft should climb if there are obstacles ahead. Generally V_x reduces for lower aircraft weights.

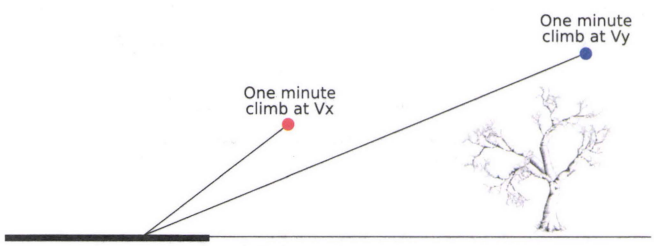

Figure 11.6: Climbing at V_x and V_y

Best Rate of Climb (V_y)**.** This speed is the one at which the aircraft will reach a particular altitude in the least time. In the absence of obstacles, this is the speed at which a normal climb after takeoff is performed. Generally V_y reduces for lower aircraft weights.

Figure 11.6 illustrates the path of two identical aircraft taking off from the same position, one climbing at V_x and the other at V_y. In the first 60 seconds, the aircraft flying at V_y has gained more altitude, but has passed much closer to the obstacle at the end of the runway.

Manoeuvring Speed (V_a)**.** This speed is the stall speed at the maximum legal G-acceleration and is therefore the maximum speed at which abrupt, full deflection of a single control cannot cause the aircraft to exceed its stress limits. Below this speed, the aircraft cannot be overstressed. Effectively, the aircraft's manufacturer guarantees that at speeds lower than V_a the aircraft will stall before structural damage can occur.

It is important to note that V_a refers to the *full* deflection of any *single* control: ailerons, elevator or rudder. Some authorities even exclude the rudder from this list but it is clear that the simultaneous use of full rudder and elevator is *not* guaranteed to avoid damage, even if made below V_a.

For most aircraft V_a depends on the weight of the aircraft, being higher at greater weights.

Exam Hint 23 *One very popular question for both flight tests and written examinations is why V_a increases with weight.*
This occurs because V_a is governed by the load factor applied to the aircraft. Consider a Cessna 172M flying at maximum gross weight of 2,300 lbs (10.23 kN) built to withstand a load factor of 3.8 (i.e., a "weight" of 3.8 times its weight in normal cruise flight)—for more details on load factors see section 9.7 on page 192. As

$$\textit{Lift} = \textit{Weight} \times \textit{Load Factor}$$

then the pilot would be safe in suddenly creating $2300 \times 3.8 = 8740$ *pounds-force (38.9 kN) of lift. If the aircraft were flying under its maximum gross weight, say at 1700 pounds-force (7.56 kN), then the same deflection of the controls would still create 8740 pounds-force of lift (since the weight doesn't affect the lift) but then the load factor that would be applied to the aircraft would be* $\frac{8740}{1700} = 5.1$*, well above the maximum of 3.8 allowed by the designer.*

Maximum Normal Operating Speed (V_{no})**.** This is also sometimes known as the maximum structural cruising speed and represents the maximum speed to be used in turbulent conditions. On many

airspeed indicators it is indicated by the upper limit of the green arc.

Never Exceed Speed (V_{ne})**.** This is the speed that the aircraft should never exceed because of the risk of structural failure. This may happen because of factors such as wing or tail deformation or aeroelastic "flutter" (unstable airframe or control oscillation). V_{ne} is indicated as a red line on most airspeed indicators.

Maximum Flap Speed (V_{fe})**.** This is the maximum speed at which the aircraft may be flown with the flaps fully extended. Many aircraft can fly at speeds greater than this with partial flap extension—refer to the operating handbook for the aircraft. The range of speeds over which flaps can be fully extended is often marked with a white arc on the airspeed indicator.

Maximum Gear Extended Speed V_{le}**.** This is the maximum speed at which the aircraft can be flown with its landing gear extended.

Maximum Gear Operating Speed (V_{lo})**.** This is the maximum speed at which the landing gear may be raised or lowered. Although it is often given as one speed, in many cases there will actually be different speeds for gear extension and gear retraction—many aircraft can extend the gear at V_{le} but must retract the gear at a lower speed. For example, the Piper Seminole can extend its gear at its V_{le} of 140 knots but must be below 109 knots to retract its gear.

Maximum Parachute Deployment Speed (V_{pd})**.** An increasing number of light aircraft are now fitted with ballistic parachutes. These can be deployed in case of emergency but never at a speed above V_{pd}.

11.4.6 Range & Endurance Speeds

Figure 9.46 on page 191 illustrates the power required for straight and level flight. It is effectively the total drag curve from figure 9.38 on page 185 multiplied by the speed of the aircraft. Two speeds can be read directly from a power curve:

1. The speed where the required power is least. This speed is known as the *Maximum Endurance* airspeed since an aircraft flying at this speed will remain airborne for the longest time while burning a given amount of fuel.

2. The speed where a tangent from the origin of the graph touches the curve. This speed is known as the *Maximum Range* airspeed since, in no-wind conditions, an aircraft flying at this speed will fly for the longest distance while burning a given amount of fuel.

Gliding, although disconcerting for a pilot of a powered aircraft whose engine has stopped, is simpler than flying with an engine. When thrust is removed, the four forces that conventionally act on a powered aircraft are reduced to three.

Figures 9.39 and 9.40 illustrate the changes in the coefficients of lift and drag at different angles of attack. The lift-to-drag ratio ($\frac{C_L}{C_D}$) is the ratio of these two values. To glide as far as possible from a given altitude (when there is no wind) the aircraft should be flown at an angle of attack that maximises the lift-to-drag ratio. The angle of attack giving the best glide performance is affected by the aspect ratio of the wing: a high aspect ratio wing[6] (e.g., on a glider) will require a somewhat higher angle of attack than a low-aspect ratio wing (e.g., on a Piper Cherokee).

If you are flying a powered aircraft that suddenly becomes a glider, then adjusting the speed of the aircraft to give the angle of attack with the greatest lift-to-drag ratio should generally be your first priority. A prudent pilot of a single-engined aircraft will be aware of both speeds and, where possible, will feather the propeller on a failed engine (i.e., turn the blades edge-on to the airstream).

Note that the drag is significantly increased by a windmilling propeller because, as the aircraft slows, the angle of attack on the propeller blade becomes negative and the "lift" produced by the propeller becomes negative thrust. For this reason the best glide speed will be different with a windmilling propeller than with a stationary propeller.

11.4.7 Slow Flight

Slow flight is flight at a speed between the Stall Speed and the Best Endurance speed. Flying in slow flight is also known as "flying behind the power curve" because, as can be seen from figure 9.46, extra power is actually needed to fly more slowly!

11.4.8 Bank/Speed vs Rate/Radius of Turn

A rate 1 turn for any aircraft is defined to be a turn that requires 120 seconds to complete 360°. Other types of turn are defined as multiples or fractions of the rate 1 turn. Thus a rate $\frac{1}{2}$ turn requires 240 seconds for a complete rotation and a rate 2 turn requires 60 seconds.

Although the time taken to complete a 360° rate 1 turn is the same for all aircraft, the angle of bank

[6] For the definition of aspect ratio see page 170.

needed to achieve the turn and the radius of the circle thus flown (in no-wind conditions) depends on the speed of the aircraft. The bank angle (B) and the radius of the turn (r in nautical miles) for different airspeeds (S in knots) are given by

$$r = \frac{S}{60\pi}$$
$$B = \tan^{-1}(60 \times 14.5808 \times 10^{-6} \times \pi \times S)$$

The strange constant 14.5808×10^{-6} that appears in this equation is actually the acceleration of gravity (normally seen as 9.8 metres per second per second) in nautical miles per hour per hour!

Figure 11.7 evaluates these formulæ for r and B at a few specific airspeeds. Note that at 400 knots a steep turn is required to achieve a rate 1 turn.

Speed (knots)	Bank Angle	Radius of Turn	Distance Flown	Time
80	12.4°	0.42 nm	2.7 nm	2 mins
120	18.3°	0.64 nm	4.0 nm	2 mins
250	34.5°	1.33 nm	8.3 nm	2 mins
400	47.7°	2.12 nm	13.3 nm	2 mins

Figure 11.7: Parameters of a 360° Rate 1 Turn

11.5 Use of Performance Charts

Exam Hint 24 *Many of the techniques described in this section require the student to interpolate in a table. Linear interpolation is described in Appendix D on page 349. Outside the examination room, a prudent pilot will often simply use the more pessimistic value. Remember also that examinations provide multiple-choice answers, and so it is often not necessary actually to perform the calculation: if you know the answer is a value between 1,322 ft and 1,543 ft and only one of the multiple choice options satisfies that requirement, then there is no need to do the arithmetic.*

11.5.1 Crosswind Charts

The AIR section of the Aeronautical Information Manual (AIM) and the CFS both contain diagrams similar to figure 11.20 which allow a wind to be resolved into its headwind and crosswind components. These are unnecessary if an aviation calculator is available.

Exercise 91 *You are about to take off from runway 32. Winds are reported as being from 290° Magnetic at 22 knots. What headwind and crosswind components can you expect?*

Exam Hint 25 *When using the CX-2 for a crosswind calculation, many students enter the runway heading rather than the runway number into the calculator (e.g., 270 instead of 27). This gives the wrong result.*

11.5.2 Takeoff & Landing Charts

The takeoff and landing distance charts in the Pilot Operating Handbooks (POHs) of various light aircraft typically take one of two forms:

1. A table of distances for various pressure altitudes and temperatures as illustrated in figure 11.10. This is common for Cessna aircraft.
2. A series of graph segments as illustrated in figure 11.9. This is common for Piper and Diamond aircraft.

Each of these types of chart is easy to use (the Piper version perhaps being the more straightforward and certainly quicker)—just follow the instructions. The Cessna version gives more precise answers but probably with no more accuracy.

Remember, however, that the takeoff and landing distances given in the POH are valid when the *maximum performance technique* as described in the POH is followed perfectly. For most of us, our technique may fall short of perfect and our aircraft may have engines that are no longer providing full power. The POH numbers are normally significant under-estimations of the actual distances required.

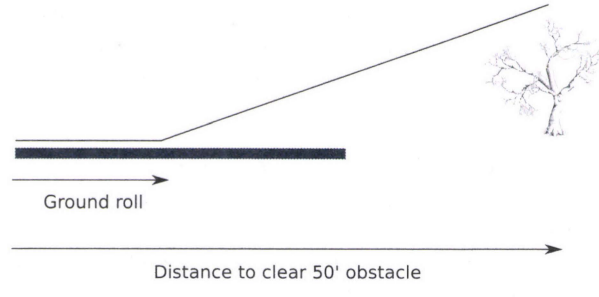

Figure 11.8: Takeoff Distances

The figures that can be derived from the tables are the amount of runway required for the takeoff or landing

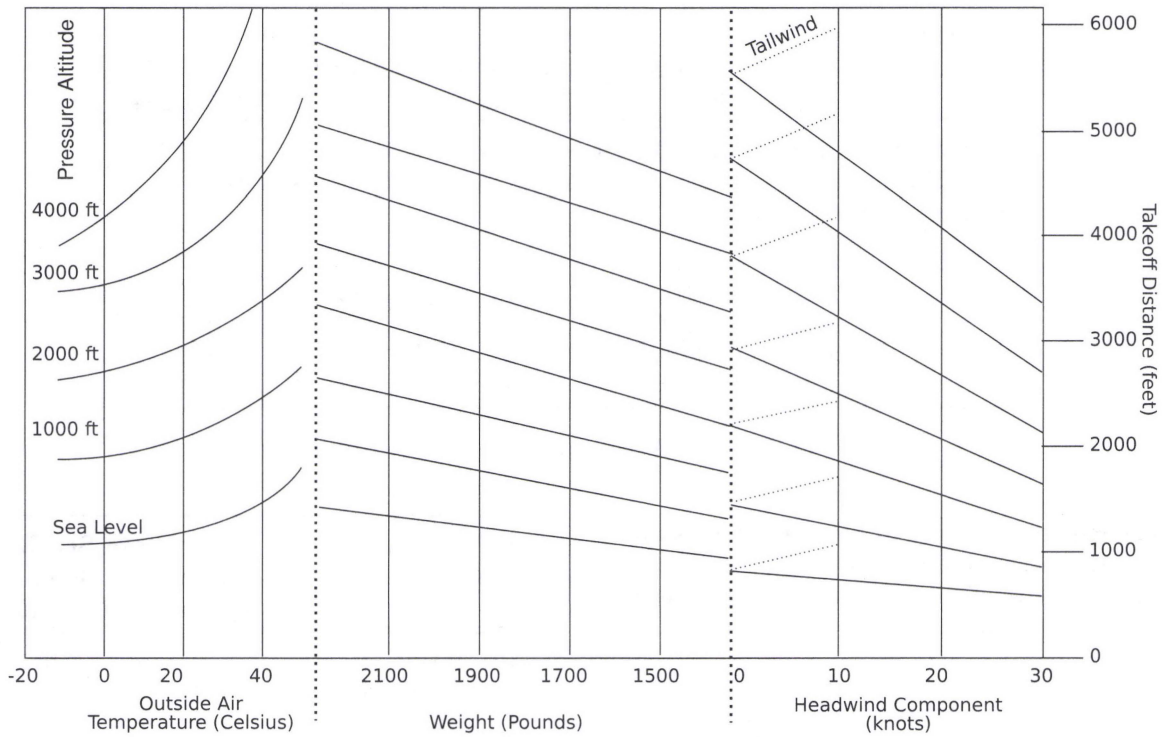

Figure 11.9: Takeoff Distance Chart for Fictitious Aircraft

and the total distance between the start of the takeoff roll and clearing a 50 ft obstacle or, in the case of landing, between clearing a 50 ft obstacle and being safely at rest on the runway: see figure 11.8. The important points to observe are the conditions under which the table is valid and any associated notes. The table for a Cessna 172M takeoff distance, for example, requires the mixture to be leaned to give maximum revolutions per minute whenever the pressure altitude is greater than 3,000 ft. If the conditions and notes do not apply then the distances given are not valid.

Exam Hint 26 *The most common mistake made under examination conditions with the takeoff calculation table is to mis-interpret the statement associated with grass runways. The Cessna 172M table, for example, says "For operation on a dry, grass runway, increase distances by 15% of the 'ground roll' figure". Once the aircraft is off the runway, whether it left grass or pavement is irrelevant. The whole distance to the 50 foot obstacle is not reduced by 15%, only by 15% of the* ground roll *figure.*

Exercise 92 *Using the chart in figure 11.9, calculate the takeoff distance for the aircraft given an outside air temperature of* $20°C$*, a pressure altitude of 1,500 ft and a 5 knot tailwind. The aircraft is loaded to 1,800 lbs.*

Exercise 93 *An airport is situated 1,000 ft above sea level. The sea-level pressure is currently* $29.42''$ *Hg and the airport temperature is currently* $18°C$*. Runway 27 is grass and the wind is 23 knots from* $290°$ *Magnetic. Using the extracted portion of the Cessna 172M takeoff distance figures given in figure 11.10, calculate the takeoff distance and the distance to climb to 50 ft in a fully-loaded (2,300 lbs) Cessna 172M.*

11.5.3 Climb Charts

Climb charts provide estimates for the time, fuel burn and ground distance covered during a climb. To use the chart, the pilot needs to know the density altitude of the departure aerodrome and the density altitude of cruise. In some Pilot Operating Handbooks (e.g., those for Cessna 172s), rather than providing the density altitudes, the pilot provides the pressure altitudes and temperatures. These charts normally present data in one of two ways:

Weight (lbs force)	Pressure Alt (ft)	10°C		20°C	
		Ground Roll (ft)	Total to Clear 50' Obstacle	Ground Roll	Total to Clear 50' Obstacle
Note: Decrease distances by 10% for each 9 knots headwind Note: For operation on a dry, grass runway, increase distances by 15% of the ground roll figure					
2300	Sea Level	835	1475	895	1575
	1000	915	1615	980	1725
	2000	1000	1770	1075	1895
	3000	1100	1945	1180	2085
	4000	1210	2145	1300	2305

Figure 11.10: Extract from Cessna 172M Takeoff Distance Table

1. the time required to climb to a particular pressure altitude from a pressure altitude of 0 ft (e.g., it takes 2 minutes to climb to 1,000 ft, 3.5 minutes to climb to 2,000 ft, etc.)
2. the rate of climb that can be expected at each pressure altitude (e.g., at 0 ft a climb rate of 650 ft/minute can be expected, at 1,000 ft a climb rate of 600 ft/minute can be expected, etc.)

The first of these types is the simpler to use and is the type described in the remainder of this chapter.

Exercise 94 *Determine the time taken, fuel consumed and distance covered by a Cessna 172M at maximum gross weight (2,300 lbs-force) climbing from an aerodrome at 3,000 ft pressure altitude to cruise at 8,000 ft pressure altitude. The temperature on the ground is 25° C.*

The table is contained in section 5 of the Cessna 172M Pilot Operating Handbook and the relevant portion is reproduced as figure 11.11.

Exam Hint 27 *The two most common mistakes that students make in an examination when using the climb charts are:*

1. *to use heights above sea level rather than pressure altitudes.*
2. *to forget that the pressure altitude of the departure airport is possibly already above sea level—subtract the time in the table needed to climb from sea level to the pressure level of the airport from the total time needed to reach the required cruising altitude.*

Pressure Altitude	Temp °C	From Sea Level		
		Time (mins)	Fuel (US gals)	Dist (nm)
S.L.	15	0	0.0	0
1000	13	2	0.3	2
2000	11	3	0.7	4
3000	9	5	1.1	7
4000	7	7	1.5	9
5000	5	9	1.9	12
6000	3	12	2.3	16
7000	1	15	2.8	19
8000	-1	18	3.3	23
Increase time, fuel and distance by 10% for each 10° above standard temperature				

Figure 11.11: Extract from Cessna 172M Climb Table

11.5.4 Cruise Charts

Cruise charts differ in format between aircraft types.

For aircraft with fixed pitch propellers, they allow the pilot, given the density altitude (or pressure altitude and temperature) and power setting of cruise, to determine the expected fuel burn, propeller rotation speed and airspeed. A Cessna 172M, for example, cruising at 10,000 ft pressure altitude when the temperature is 20° below standard at 69% power, could expect to burn 7.6 gallons of fuel per hour, have a propeller speed of 2600 rpm and achieve a speed of 115 knots TAS.

For aircraft with constant speed propellers, the pilot supplies the density altitude (or pressure altitude and temperature), propeller rotation speed and manifold pressure and the table returns the fuel burn and true airspeed. A Cessna 182, for example, when flying at 15,000 ft at 2,300 rpm with 16″ of manifold pressure, would burn 9.6 gallons of fuel per hour and cruise at 143 KTAS.

11.5.5 Fuel Burn Charts

The rate of fuel burn is taken from the cruise and climb/descent tables.

11.5.6 Runway Surfaces

A Pilot Operating Handbook (POH) will contain landing and takeoff distance values calculated for dry, paved, level runways. Given these basic numbers, corrections need to be made for the actual runway conditions:

- **Grass surface.** The POH will typically provide an adjustment to be used on short, dry grass. The Cessna 172M manual, for example, states that 45% of the ground roll figure should be added to the basic numbers in the table when landing on a dry grass runway.

  Transport Canada has published guidelines estimating the effects of various runway surfaces on takeoff distances. These are reproduced as figure 11.12 but should be taken as approximations.

  The effect of long grass is not calculable, though the longer and denser the grass the more effect it will have in retarding the aircraft's acceleration and increasing the distance required for takeoff.

- **Ice, Snow & other Contaminants.** See section 11.8.2.

Surface	Takeoff Distance Factor
Paved	×1.00
Firm Turf	×1.07
Rough Surface, Short Grass	×1.10
Long Grass (over 4″)	×1.30
Soft Mud or Snow	×1.75

Figure 11.12: Estimated Effects of Runway Surfaces

11.5.7 Up/Downslope Runway

When an aircraft takes off from a sloping runway, part of the aircraft's weight vector effectively becomes additional drag (on upsloping runways) or thrust (on downsloping runways). It is easy to calculate the additional drag or thrust given the weight of the aircraft:

$$\text{additional drag or thrust} = w \times \sin(\theta) \qquad (11.1)$$

where w is the weight of the aircraft and θ is the angle of the runway to the horizontal.

Exercise 95 *A Cessna 172M fully loaded at 2,300 lbs takes off from a runway sloping upwards at 3° to the horizontal. What additional drag does it experience?*

As a rule of thumb, many pilots estimate the advantage or disadvantage of a sloped runway by assuming that a 1° runway gradient is equivalent to a 10% increase or decrease in effective runway length. So a 3,000 ft runway with a 3° uphill gradient should be thought of as a 2,100 ft runway. This is very much a simple rule of thumb and should not be considered accurate for all aircraft. As illustrated in example 95, the effect of an upslope depends on the excess power that the aircraft has available. A fully laden Boeing 777, for example, would have a weight increase of approximately 152,616 Newtons (34,309 lbs force) on a runway with a 3° upslope. This represents 22% of its engine power. An ultralight on the same runway might experience a weight increase of 231 Newtons (52 lbs force) and this is 17% of the engine power. So the slope would affect the ultralight less than the Boeing 777.

Anecdote 39 *I am often asked whether, when flying a light aircraft with which I'm familiar, I calculate a runway distance before every takeoff and landing. The answer is strictly "yes". However, when I am taking off reasonably loaded on a 3,000 ft runway on a normal day, the calculation was done a long time previously, and I don't repeat it. In unusual circumstances, I do perform the calculation. For example, I once asked for the aircraft to be half-fuelled when departing from Marlboro, USA (K9B1) on a hot day. However, the FBO had completely filled the tanks. The runway is 1,659 ft long and, taking off to the northwest, the departure end almost reaches a road with large trucks passing. Some joker had even placed a HALT sign at the end of the runway. In that circumstance I did the calculation* very *carefully.*

11.6 Weight & Balance

11.6.1 Calculation

Calculating an accurate weight and balance at takeoff (and, for some aircraft, at landing) is essential for a safe flight. There are two basic concerns:

1. **Weight.** Is the aircraft under its maximum gross weight? If not, the aircraft is not guaranteed to take off. Even if the aircraft *is* under its maximum gross

weight, there may be conditions of density altitude for which takeoff is not guaranteed. For example, when it is at maximum gross weight, a pressure altitude of 7,000 ft and a temperature of 30°C, the Cessna 172M has no takeoff distance defined. Under these conditions Cessna makes no guarantee that the aircraft will lift off at all and, if it does lift off, makes no guarantee about its rate of climb.

2. **Balance.** Is the Centre of Gravity[7] of the aircraft within its allowable range?

Calculation of both weight and balance is simple when three terms are understood:

1. **Weight.** Weight is a force measured, for aeronautical purposes in North America, in pounds-force (often shortened to just "pounds"). There are several standard weights associated with an aircraft:

   Empty weight, which includes airframe, engine, standard equipment and options but no fluids

   Standard Empty weight, which includes the airframe, engine, standard equipment and unusable fuel/oil

   Basic Empty weight, which includes airframe, engine, installed equipment, full oil and unusable fuel

   Licenced Empty Weight, which is the basic empty weight with all the oil, except for that which cannot be drained, removed

   Gross weight, which is the maximum weight that the aircraft is allowed to be at take off, including passengers, pilot and cargo

2. **Arm.** The distance between a force and the pivot point around which the balance is being measured. For Cessna aircraft, the pivot point is normally the fire-wall at the back of the engine and so arms are measured from that point. For other aircraft, the pivot point may be the tip of the spinner or, indeed, any other point in space. In North America, arms are measured in inches.

3. **Moment.** A small force acting with a large arm may apply as much turning moment as a large force acting with a small arm. This is why it is easier to turn a nut with a long spanner than with a short one or why a heavy boy sits closer to the pivot than a small girl with whom he is playing on a seesaw.

[7]Centre of Gravity is more accurately called the "Centre of Mass". You could expect either term in an examination.

The weight and balance of an aircraft can be calculated using a table[8] of the type shown in figure 11.13:[9]

- Complete the weight and arm columns by weighing yourself, passengers and luggage (don't simply ask your passengers for their weight—people lie or assume that you mean their weight on their bathroom scales in the morning, when they were more lightly clad than they will be in the aircraft). Decide how much fuel you will have on board and enter this for the fuel row.

- Multiply the weights and the arms and fill these in under the moment column. In some books you may see the moments in kilo-pound inches (klb-in)—calculated by dividing the moment by 1,000. There seems to be no useful reason for doing this.

- Add up the weight and moment columns. Adding up the arms makes no sense—don't do it.

- Check the total weight and moment against the diagram shown in the Pilot Operating Handbook. For some aircraft two areas are given: Utility and Normal categories. Unless the aircraft is in one of these categories, the aircraft must *not* be flown. Unless the aircraft is in the utility category no aerobatic manoeuvres (including stalls and spins) may be flown.

11.6.2 Segmented Weights

The calculation of total passenger weight described above is practical for a very small aircraft, but impractical for a commercial operation. For such a situation, passenger weights can be determined by:

- Actual weights measured at the airport.

- If a passenger is not willing to be weighed, then he or she can be asked to volunteer the weight and this must be checked as being reasonable by the person carrying out the boarding.

- If there are too many passengers for individual weights to be assessed, then standard weights of 206 lbs for a male passenger in the summer, 212 lbs for a male in the winter, 172 lbs for a female passenger in the summer and 178 lbs for a female in the winter may be used.

[8]A spreadsheet is an obvious tool for this.

[9]The numbers in **bold** in that table are taken from the Pilot Operating Handbook; the numbers in *italics* are taken from the aircraft's weight and balance report.

Item	Weight (lbs)	Arm (inch)	Moment (lb-inch)	Notes
Aircraft Basic Empty weight	*1412*	*39.1*	55209	Not taken from the POH: must come from the aircraft's own Weight and Balance Report
Fuel	228	**47.8**	10898	38 gals at 6 lbs/gal
Pilot	180	**37**	6660	
Front-Seat Pass.	165	**37**	6105	
Back-Seat Pass. 1	170	**73**	12410	
Luggage (back seat)	25	**73**	1825	
Luggage	10	**95**	950	
TOTALS	2210	-	94057	

Figure 11.13: Example Weight and Balance

- For air taxi operations (see section 14.7.4 on page 329 for a description of air taxi operations) standard weights may not be used. If actual weights are not available, then segmented weights must be used; see figure 11.14. This table is used as follows:

  1. Select the row from the table corresponding to the maximum certified passenger seating capacity for the aircraft (not the number of seats that are actually occupied).
  2. For each passenger, assume the weight given in the table, according to season.
  3. Add up all the weights: this is the passenger weight that must be used.

Max. Seats	Winter		Summer	
	Females	Males or Gender X	Females	Males or Gender X
1 - 4	Must use actual weights			
5	210	249	204	243
6-8	206	244	200	238
9-11	199	236	193	230
12-16	196	233	190	227
17-25	193	229	187	223

Figure 11.14: Segmented Weights Chart (lbs)

Exercise 96 *A King Air B100 capable of carrying 13 passengers is being used for an air taxi operation in Canada during January. There are 5 female and 3 male passengers on board. What total passenger weight should be assumed?*

11.6.3 Weight Shift Formula

It sometimes occurs that once the calculation illustrated above is performed, it is found that the gross weight is within limits but the centre of gravity is too far back. In this case items must be moved forward (e.g., luggage from the baggage compartment moved to the back seat). To check that this will have the desired effect, it is probably simplest to rework the numbers in figure 11.13. There is, however, a formula (the weight shift formula) that will immediately tell you whether the movement is sufficient:

$$\text{dist CofG moves} = \frac{\text{weight} \times \text{dist moved}}{\text{aircraft weight}} \qquad (11.2)$$

Exercise 97 *You move a box weighing 55 lbs from the luggage compartment of your aircraft (an arm of 123 inches) onto the back seat (an arm of 73 inches). If the total weight of the aircraft is 2,134 pounds-force then how far will the centre of gravity of the aircraft move?*

11.6.4 Change of Centre of Gravity

The primary effects of a change in the position of the centre of gravity of an aircraft are on the stall behaviour and its cruise range.

In many aircraft, the further that the centre of gravity moves backwards, the lower the stall speed. The Pilot Operating Handbook for a Cessna 172M, for example, gives the stall speed with flaps up and no banking as 42 KIAS with the most rearward permitted centre of gravity and 47 KIAS with the most forward centre of gravity. Once the centre of gravity is outside the permitted range, the aircraft can become seriously unstable—possibly not being able to recover from a stall should it occur.

To obtain maximum range, most aircraft can be loaded so that the centre of gravity is close to its rearward allowed limit. This allows the tailplane to be more lightly loaded, and therefore generate less induced drag.

Having the centre of gravity too far back can also cause longitudinal instability—see section 9.8.4 on page 194.

11.7 Wake Turbulence

11.7.1 Causes

In summary, wake turbulence forms behind an aircraft, primarily from two causes:

1. *Wingtip Vortices,* caused as a byproduct of lift. Wings of fixed-wing aircraft and rotors of helicopters give lift primarily by causing air to move downwards, causing lift in accordance with Newton's third law of motion. There is also a general flow of air from the fuselage end of the wing towards the tip on the lower surface of the wing: see figure 9.23 on page 178. As pressures above and below the wing are different, the actual flow above and below the wing occurs at different angles. When these two flows meet at the trailing edge, vortices form and move outwards towards the wingtips.

   At altitude these vortices sink at a rate of about 100 to 150 metres per minute and stabilise about 150 to 250 metres below the generating aircraft.

   Wing-tip vortices are described in more detail in section 9.4.3 on page 178.

2. *Jetwash,* the rapidly moving air expelled from a jet engine.

Jetwash tends to be extremely turbulent but doesn't last long. Wingtip vortices, on the other hand, are much more stable and can remain for several minutes after the passage of an aircraft. Wingtip vortices are the more dangerous form of wake turbulence with vortex tangential speeds exceeding 100 metres per second having been recorded.

Wake turbulence is particularly dangerous during landing and takeoff as, at these times, aircraft operate at low speeds and high angles of attack, requiring more lift from the wings and therefore creating stronger wingtip vortices. The greatest vortex strength occurs when the generating aircraft is heavy, clean (i.e., flaps and wheels retracted) and slow.

In recent years, ground-installed Doppler Lidar devices have become available to detect wake turbulence and wind shear. These detect air movement by pulsing laser light in the near infrared (NIR) band. The light scattered back by moving dust particles is collected and a signal processor calculates the Doppler shift of the collected light, averages the results over a number of laser pulses and derives a Doppler shift that is an estimate of the speed at which the air is moving.

These devices are not yet available at most airports so timing is used to help prevent vortex problems. Aircraft are categorised by their maximum takeoff mass (MTOM): see figure 14.9 on page 332.

A strong or gusty wind tends to break up vortices quite quickly but a steady wind of between 1 and 5 knots can often blow the vortices across a parallel runway. The most dangerous condition is a light, quartering tailwind on the generating aircraft as it lands. Under these conditions the vortices themselves can get into ground effect and be carried significant distances.

11.7.2 Effects

A light aircraft flying into the vortices generated by a heavy aircraft can easily be overturned and forced into the ground. However, it is not only light aircraft that can be destroyed by wing-tip turbulence: in November 2001, American Airlines Flight 587 crashed in New York shortly after takeoff from John F. Kennedy International Airport. This accident was blamed on the presence of wake turbulence from a Japan Airlines Boeing 747.

11.7.3 Avoidance

The greatest potential for an accident caused by wake turbulence occurs when a light aircraft turns from base to final behind a heavy aircraft flying a straight-in approach. Since vortices descend behind the generating aircraft, pilots must intercept the final approach path above or well behind the heavier aircraft.

In general during landings, the pilot of the light aircraft should stay well above the glidepath of the heavy aircraft and land beyond the point where the heavy aircraft touched down. For a takeoff, the pilot of the light aircraft should ensure that his or her aircraft takes off well before the point at which the heavy rotated and should move to the left or right of the heavy's path as soon as it is safe to do so. Many pilots are aware of the wake turbulence issue when directly following a heavy aircraft but forget that they can also be seriously impacted when passing behind and below a heavy aircraft landing on or taking off from a cross-runway.

11.8 Winter Operations

11.8.1 Runway Surface Condition NOTAM

The general format of a NOTAM is given in section 6.4.3 on page 122. This section describes a type of NOTAM of particular interest in the winter: the NOTAM that reports the condition of a runway surface. Before August 2021, this type of NOTAM was called a NOTAMJ or SNOWTAM, but those terms are no longer used.

A Runway Surface Condition (RSC) report contains a description of any contamination on the runway (e.g., $\frac{1}{2}$ inch of dry snow) and a Runway Condition Code (RWYCC) giving guidance on the amount of control and braking action a pilot will meet when landing or manœuvring on the runway.

For long runways, the conditions are described for each third of the runway as in this example:

```
(S2867/24 NOTAMR S2835/24
A) CYOW B) 2401141230 C) 2401142030
E) RSC 07 3/6/6 50 PCT 1/2IN DRY SNOW, DRY, DRY.
160FT WIDTH. REMAINING WIDTH 1IN DRY
SNOW. VALID JAN 14 1157 - JAN 14 1957.

RSC 25 6/6/3 DRY, DRY, 50 PCT 1/2IN DRY SNOW.
160FT WIDTH. REMAINING WIDTH 1IN DRY
SNOW. VALID JAN 14 1157 - JAN 14 1957.
```

This indicates that:

- the first third of runway 07 has a RWYCC of 3 (see below) and 50% of it is covered with $\frac{1}{2}$ inch of dry snow.
- the second and third thirds of runway 07 have a RWYCC of 6 and are dry.
- these reports on the thirds of the runway refer to the 160 feet wide portion that has been cleared. The remaining width of the runway is covered in one inch of dry snow.

The conditions for each third of runway 25 are, of course, the mirror image of those for 07.

This type of NOTAM is not issued in the summer when a runway has standing water on it, caused by rain. However, that type of runway can also be a hazard: see the description of hydroplaning in section 11.3.8 on page 238.

11.8.2 CRFI & RWYCC

Traditionally, the effect of snow and ice on the braking action for aircraft has been reported as a Canadian Runway Friction Index (CRFI). A CRFI is not issued for a runway which is slippery only because of water lying on it.

The CRFI is measured by driving a test vehicle fitted with an accelerometer along the runway within 30 ft of the runway centreline and, at intervals of approximately 1,000 ft, applying the brakes. The accelerometer measures the effectiveness of the braking on a scale between 0 (effectively, no braking at all) and 1 (perfect braking).

The Airmanship (AIR) section of the Aeronautical Information Manual (AIM) contains tables estimating the additional landing distance required for particular values of the CRFI: figure 11.15 is extracted from one of these tables. The AIM states that these values have a 95% confidence level (i.e., they should be conservative for 19 landings out of 20) although the described methodology of discarding the most pessimistic 5% of the test data does not seem to be a statistically valid way of deriving a confidence level. The numbers were obtained from a series of full anti-skid braking runs with a Falcon 20 aircraft on various contaminated runway surfaces. Some runs were landings with full flaps, while others were rejected takeoffs with partial flaps. Even though the values were only measured for the Falcon 20, it is believed that they are accurate for other aircraft.

Exercise 98 *Given the current wind conditions, an aircraft would require a landing distance of 2,200 ft on a clean runway. The CRFI is reported to be 0.27. Using figure 11.15, estimate its approximate landing distance.*

Normal Landing Distance	CRFI 0.50	0.40	0.30	0.25	0.20	0.18
1800 ft	3300	3540	3900	4150	4470	4620
2000 ft	3690	3980	4410	4700	5070	5250
2200 ft	3960	4280	4750	5080	5490	5700
2400 ft	4370	4740	5260	5620	6080	6300
2600 ft	4750	5160	5740	6130	6630	6870

Figure 11.15: Landing Distances by CRFI Values

In addition to the landing distance, the CRFI will affect the maximum amount of crosswind that can be tolerated for a takeoff or landing. Section AIR of the AIM contains estimates for pairs of values ranging from no crosswind at all when the CRFI is 0.1 to 45 knots crosswind when the CRFI is 0.75. This does not mean that, if your aircraft's demonstrated crosswind limit for

landing is 15 knots, you will be able to land in a 45 knot crosswind when the runway is slightly slippery!

Figure 11.16 gives some indications of the ranges that the CRFI can take for different runway conditions.

Surface	CRFI Range
Dry snow on packed snow	0.12 to 0.37
Dry snow on ice	0.08 to 0.27
Dry snow on pavement	0.16 to 0.76
Sanded Packed Snow	0.23 to 0.47
Bare packed snow	0.12 to 0.31
Sanded ice	0.19 to 0.35
Bare ice	0.07 to 0.22

Figure 11.16: Ranges of CRFI Values

As can be seen from the examples in section 11.8.1, the main part of a NOTAM now contains a Runway Condition Code (RWYCC) rather than a CRFI. This is similar to the CRFI, but rather than being a value between 0 (no braking) and 1 (perfect braking), the RWYCC is a number between 0 (no braking) and 6 (perfect braking). The RWYCC also differs from the CRFI in that it is used when the runway is wet, with no contamination other than water. There is no direct mapping between CRFI and RWYCC, but they are roughly as listed in figure 11.17.

A RWYCC of ...	corresponds to a CRFI of ...
6	≥ 0.40
5	≥ 0.40
4	0.39 to 0.35
3	0.34 to 0.30
2	0.29 to 0.20
1	< 0.2

Figure 11.17: RWYCC to CRFI: Approximate Equivalences

CRFI values do not form part of the standard NOTAM format (Global Reporting Format — GRF), but are often included as non-GRF information on a NOTAM in the following format:

```
ADDN NON-GRF/TALPA INFO:
CRFI 01 -4C .45/.47/.44 OBS AT 2412232200.
CRFI 19 -4C .44/.47/.45 OBS AT 2412232200.
```

This indicates that, for runway 01, the temperature was $-4°C$ and the CRFI values for the three thirds of the runway were 0.45, 0.47 and 0.44. The measurements are from 22:00Z on the 23rd December 2024.

11.8.3 The Clean Aircraft Concept

Transport Canada's Airworthiness Notice B017 defines the concept of the "clean aircraft". The CARs prohibit taking off when frost, ice or snow is adhering to any critical surface of the aircraft. This is referred to as "The Clean Aircraft Concept". The definition of *critical surface* is "wings, control surfaces, rotors, propellers, all stabilisers and, if the aircraft has rear-mounted engines, the upper surface of its fuselage."

Transport Canada has produced a number of booklets and videos under the general title of *"When In Doubt... Aircraft Critical Surface Contamination Training—Ground Crew, Small Aircraft and Large Aircraft"*. These should be obtained and studied.

11.8.4 Frozen Contaminants

Many factors affect how frozen contaminants accumulate on the aircraft surface. Some may be removed by physical actions (e.g., removing loose snow by compressed air or nitrogen blasts) but many require the application of freezing point depressant (FPD) fluids. These should not be used unless explicitly approved by the aircraft manufacturer. Their holdover times (during which they continue to be effective) should be noted—measured from the start of the final application of fluid.

11.8.5 Aircraft Inspection

Where frost, ice or snow may reasonably be expected to adhere to the aircraft, the CARs require that a visual inspection be carried out before a takeoff is attempted. The types and minimum number of inspections are indicated by the regulations, and depend on whether or not the operator has an approved Operator's Ground Icing Operations Programme using the Ground Icing Operations Standard as specified in CAR 622.11.

The pilot-in-command has the ultimate responsibility to determine whether or not the aircraft is in a suitable condition for safe flight.

Other items that must particularly be checked during the pre-flight inspection in cold weather include:

- a check for water contamination of the fuel. If fuel tanks are not completely full of fuel then moisture can condense out of the air and contaminate the fuel.
- a visual check of the viscosity of the engine oil. If necessary, the oil will need to be heated before engine-start.
- an inspection of the fire extinguisher(s) in accordance with the manufacturer's handbook.

Many types of fire extinguisher become ineffective after prolonged storage at very low temperatures.

- a close inspection of the static ports to ensure that they have not become frozen over.

At the beginning of a flight when the aircraft has been standing in the cold, sufficient time must be given before takeoff for the avionics to reach normal operating temperatures. This may take as long at 20 minutes for some aircraft. Before that time, displays may be dim or even inoperative.

Following a flight, if the aircraft is to be left in an unheated area, then special actions may be specified in the Pilot Operating Handbook: typically, toilets should be drained (or have glycol added to their fluid), the battery (particularly if nickel-cadmium) may have to be removed and parking brakes probably should not be applied. All types of batteries should be kept fully charged when the aircraft is left in cold conditions.

If the aircraft is to be stored in a warm hangar after a flight in cold weather, fuel tanks should not be completely filled because the fuel may expand and leak from the tanks in the hangar causing a fire hazard.

11.8.6 Engine Starting

With reciprocating engines without FADEC,[10] during engine start in cold conditions there is a tendency to over-prime. This excess fuel washes down the cylinder walls and scoring may result. It also results in poor compression and, consequently, hard starting.

Another cold start issue that affects unheated reciprocating engines is that of icing over the spark-plug electrodes. Typically the engine fires for a few revolutions and then quits. There has been sufficient combustion to cause some water to accumulate in the cylinders but insufficient combustion to heat them up. This water condenses on the spark-plug electrodes, and shorts them out. The only remedy is heat. When no large heat source is available, the plugs should be removed from the engine and heated to the point where all the moisture has evaporated.

11.8.7 Cold Soaking

Cold soaking occurs when an aircraft has flown for some time at altitude so that the temperature of the fuel and airframe has dropped below 0°C. Once the aircraft has landed, liquid rain or mist may condense into ice on the cold surfaces even though the outside air temperature is above freezing point. This is particularly true around wing-mounted fuel tanks since fuel will typically take longer to warm up than other parts of the aircraft. The clear ice that often forms in this process is very difficult to detect visually and may break loose during or after takeoff, damaging control surfaces.

[10] See section 12.3.6 on page 267 for a description of FADEC.

11.8.8 Runway Contaminants

When taxiing in slushy conditions, brakes should not be used more than is absolutely necessary. "Riding the brakes" can cause the brakes to heat up and ice on them to turn to water. Once airborne, this water can re-freeze and lock the brakes during landing.

During takeoff in slush, a slush and water bow wave forms in front of the main wheels, growing in size with increasing speed. The acceleration during the low speed portion of the takeoff roll is about normal but deteriorates as rotation speed is approached. In addition, it is possible to sustain damage on the lower fuselage and wing area from the slush thrown up from the wheels.

11.8.9 Inflight Icing

The different types of ice (rime, clear and frost) and the mechanisms by which they adhere to aircraft on the ground and in flight are described in section 4.14 on page 86. This section covers some of the operational aspects of dealing with ice.

The major effects of ice forming on airframes include:

- **A loss of lift and increase in stall speed and drag.** Tests carried out by Transport Canada indicate that frost, ice or snow formations having a thickness and surface roughness similar to medium or coarse sandpaper on the leading edge and upper surface of a wing, can reduce wing lift by as much as 30% and increase drag by 40%.

  The resultant loss of lift and increase in drag has been responsible for numerous aircraft crashes, some for the reason shown in figure 11.18. Without ice, the full power cruise speed when using a normally-aspirated engine decreases with altitude. Normally, the altitude at which the cruise speed becomes the same as the stall speed is well above the aircraft's ceiling. However, as the drag on the aircraft increases, so the full power cruise speed at a particular altitude decreases. Also, as the wing shape is changed by ice building up, its stall speed increases. The situation can occur as illustrated in figure 11.18 where the stall speed has reached the maximum cruise speed at an altitude where the aircraft normally flies. When this occurs, the only option is to descend.

- **Induction Icing.** Ice building around the air intake to an engine can cause the engine to lose power and, eventually, stop. An analysis of the

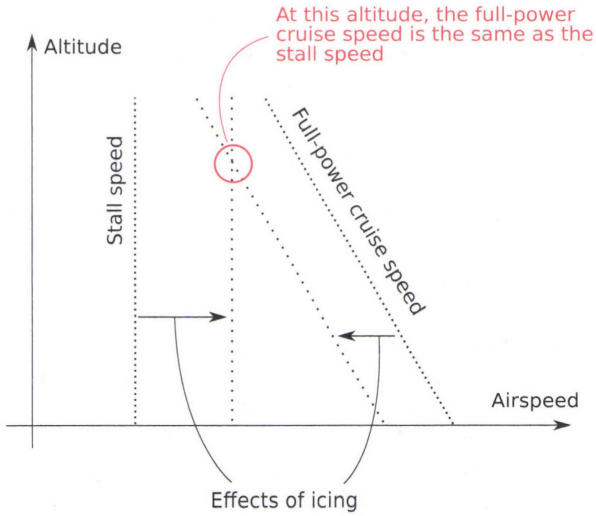

Figure 11.18: Effects of Icing

AOPA Air Safety Foundation Accident database shows that, during the period 1990 to 2000 in the USA, 52% of the icing-related accidents were caused by induction icing—a larger proportion than the 40% caused by structural icing.

- **Locking of Control Surfaces.** Water flowing back across a wing or tailplane and freezing in the hinges can restrict the movement of the control surfaces.
- **A loss of thrust.** Ice adhering to propellers and disturbing the airflow by forming around the cowling can both cause loss of thrust. In aircraft with a constant-speed propeller, rapidly changing the RPM may cause the ice to break free as the propeller blades pivot. In jet aircraft ice ingestion may induce a compressor stall and cause a flame-out (i.e., extinguish the combustion).
- **Tailplane Stalls.** The horizontal tailplane is also a flying surface (albeit in most aircraft installed "upside down", in comparison with a wing, to give negative lift). When coated with ice the tailplane can stall, particularly when its angle of attack is increased by lowering of flaps on a high-wing aircraft, causing the aircraft to pitch violently nose-down. The National Aeronautics and Space Administration in the USA has prepared a very instructive 23 minute video entitled *Tailplane Icing* which demonstrates a tailplane stall in a light twin-engined aircraft. However, see the comment about the possible effect of this video on Colgan Air Flight 3407 described in section 1.6.4 on page 19.
- **Fuel Vent Blockage.** Fuel vents typically face into the airflow to create a positive pressure in the fuel tank to assist with getting fuel to the engine. If these freeze over then fuel may not reach the engine.
- **Antenna Vibration.** As ice forms on radio antennæ they may become unstable and start to vibrate badly, possibly breaking away.
- **Loss of Stall Warning Indicator.** The stall warning indicator on most light aircraft will be one of the first items to freeze up—to some extent this doesn't matter because it would be inaccurate anyway with ice on the wings. However, a stall with iced wings can be much more abrupt than a normal stall: transitioning from lift to no lift with a very small change in angle of attack.

If you do find yourself in icing conditions then immediately disengage the autopilot's altitude hold. When the ice reaches the point where level flight is no longer possible, the autopilot, being unaware of the icing, will try to pitch the nose up to avoid a descent. That will cause a stall. Once the autopilot is disengaged, try changing altitude—sometimes as little as 50 ft can make the difference between accumulating ice and shedding it. In particular try to find warmer air if you are accumulating ice—normally below you but sometimes above.

11.9 Search & Rescue (SAR)

11.9.1 Service Available, Request for Assistance

Search and Rescue in Canada is co-ordinated by the National Search and Rescue Secretariat (NSS), an independent agency of government reporting to the Department of Public Safety and Emergency Preparedness. The NSS was established in 1986 to achieve highly effective and economically responsible search and rescue programmes throughout Canada.

Search and Rescue service is provided throughout the whole of Canada and Canada's territorial waters from three Rescue Co-ordination Centres (RCCs) located in Victoria (British Columbia), Trenton (Ontario) and Halifax (Nova Scotia). The telephone numbers of these centres are to be found in the SAR pages of the AIM. If you suspect that an aircraft is overdue then you should contact the nearest RCC or air-traffic control centre without delay.

11.9.2 Aiding Persons in Distress

Whenever possible, pilots should monitor 121.5 MHz and listen for the characteristic sound of Emergency Locator Transmitters (ELTs). 406 MHz ELTs also transmit these

signals on 121.5 MHz. If you hear an ELT or see an aircraft or ship in distress[11] then, if possible, you should:

1. keep the craft in sight until your presence is no longer required
2. report to an air-traffic control unit or flight service station:
   - the time of the observation.
   - the position of the craft. With most aircraft now fitted with some type of GPS unit, it should be possible to be give a precise latitude and longitude.
   - a general description of the scene.
   - the apparent physical condition of any survivors.

11.9.3 Emergency Locator Transmitters

Section 605.38 of the CARs states that, subject to some exclusions for balloons, gliders, ultralights and training aircraft operating close to an airport, *"no person shall operate an aircraft unless it is equipped with one or more ELTs"*.

The current generation of ELTs, in addition to broadcasting on 406 MHz, also emit a signal on 121.5 or 243.0 MHz when activated. The 406 MHz signal has a significantly greater power than the 121.5 MHz signal and can be detected by SARSAT and COSPAS[12] satellites; the 121.5 MHz signal can be detected by overflying aircraft. There are five categories of ELTs:

1. **Automatic ejectable** (Type A) or Automatic Deployable (Type AD). This type automatically ejects from the aircraft and starts transmitting when the aircraft is subjected to a crash deceleration. This type is expensive and seldom used in general aviation.
2. **Fixed (not ejectable)** (Type F) or Automatic Fixed (Type AF). This type is automatically set in operation when the aircraft is subjected to crash deceleration acting along the aircraft's longitudinal axis and may be manually activated by a switch on the device or on the control panel. This type of ELT is normally connected to an antenna fitted to the fuselage of the aircraft but may have an additional antenna for portable use. Most general aviation aircraft use this ELT type, which must have the function switch placed to the "ARM" position for the unit to function automatically in a crash.
3. **Automatic Portable** (Type AP). This type is similar to Type F or AF except that the antenna is integral to the unit for portable operation.
4. **Personal** (Type P). This type has no fixed mounting and does not transmit automatically. A manual switch is used to start or stop the transmitter.
5. **Water-activated** (Type W) or Survival (Type S). This type transmits automatically when immersed in water. It is designed to float and operate on the surface of the water. It has no fixed mounting and is normally tethered to survivors or life rafts.

The previous generation of ELTs only broadcast on 121.5 and 243 MHz and these were phased out before 1st February 2009 when the SARSAT satellites stopped monitoring those frequencies. This phasing out activity, and the introduction of ELTs broadcasting on 406 MHz, is thoroughly described on the Cospas-Sarsat webpage at `https://cospas-sarsat.int/en/`. The new ELTs provide significant advantages over the older, 121.5 MHz or 243 MHz varieties:

- They transmit a unique code identifying the aircraft that is transmitting the signal. This allows owners to be contacted before search and rescue is dispatched—only 2% of alerts are genuine.
- Their position is resolved by the signals picked up by the satellites after a single pass (typically five minutes) rather than requiring two passes (typically ninety minutes).
- The resolution of location is much finer (5 km or a few metres if GPS is included) rather than 20 km.

ELTs, whether broadcasting on 121.5, 243.0 or 406 MHz, are line-of-sight devices. To achieve the best range, the transmitter should be placed as high as possible on a level surface. Raising an ELT from ground level to 2.4 metres increases its range by up to 40%. The antenna should be held vertical and placing the transmitter on a piece of metal (e.g., the wing of the aircraft if it is level) provides reflectivity to increase the transmission range.

ELTs may be tested for periods of up to 5 seconds in the first 5 minutes of any UTC hour. If an ELT is accidently activated at any other time, then an FSS should be notified to prevent unnecessary search and rescue.[13] If an ELT is removed from an aircraft then it

[11] Small boats signal distress by displaying a rectangular, fluorescent orange-red cloth panel on which a black square and disc is displayed. If you are flying over water you should look out for these.

[12] The COSPAS-SARSAT satellite system was launched in 1982 by Canada, France, the USA and the former USSR. It has helped to save over 50,000 lives world-wide.

[13] Note that most ELTs do not start broadcasting for the first 50 seconds after being turned on, so turning off within that period should be OK. However, a call to a FSS would always be the best option.

should always be turned *OFF* to prevent spurious alarms.

Various private companies offer services considered by some pilots to be of more value than ELTs. An ELT provides no information about the whereabouts of the aircraft until the time of the crash. The pilot might activate the ELT immediately before the crash or it might be automatically activated by the impact, but unfortunately, in many cases, neither occurs. If the crew of the aircraft is incapacitated by the crash, then the ELT may never be activated.

Companies such as SPOT[14] and Zoleo[15] offer an alternative service. The SPOT or Zoleo device (see figure 11.19) transmits its position, determined by GPS, to a base station through the satellite telephony service at regular intervals. In addition, pressing a button on the device causes an alert to be signalled at the base station to cause the personnel there to launch the appropriate rescue service.

The main advantage of this type of unit over an ELT is that if it is destroyed in the crash, it has left a trail of position reports to lead the search and rescue crews to the crash site. In the field "Tracking URL", the NAV CANADA website for filing a flight plan allows the pilot to enter the URL provided by SPOT or Zoleo where the location of the device can be found.

The primary disadvantage of these devices is that they do not activate automatically in the case of a crash.

Figure 11.19: Zoleo & SPOT Locators

Anecdote 40 *My wife and I often take our Cessna 172 along the north shore of the St Lawrence river from Ottawa to Labrador. Although there is neither secondary radar nor cellular telephone coverage for much of this route, using our SPOT transmitter we are able to send position reports to family members in the UK and Australia while on the ground and in flight. The messages arrive by email within a few seconds of us activating the device and give our family the reassurance of knowing our precise position.*

[14] http://www.findmespot.ca/en/
[15] https://www.zoleo.com/en-ca

11.9.4 Emergency Assistance

An emergency condition is classified as being:

- a condition of being threatened by serious and/or imminent danger and requiring immediate assistance. This is indicated by using the term *MAYDAY* three times on the radio at the beginning of the emergency call.

- a condition concerning the safety of an aircraft or other vehicle, or of some person on board or within sight, which does not require immediate assistance. This is indicated by speaking the term *PAN PAN* three times on the radio at the beginning of the emergency call.

These calls would normally be made on the air-traffic control frequency already in use. Failing that, the international emergency frequency of 121.5 MHz should be used. In addition to making radio calls, emergencies can also be declared by squawking specific transponder codes:

- 7700 indicates an emergency (equivalent either to a MAYDAY or PAN PAN). Note that, if an emergency occurs in flight, it may be quicker and easier to squawk 7700 than make a MAYDAY call, particularly as many transponders switch to 7700 on a single button-push.

- 7600 indicates a loss of radio communications. Clearly in VFR conditions in uncontrolled airspace the loss of a radio is of little concern to anyone other than the pilot thinking of the cost of repairs. In this case 7600 should *not* be used. However, in IMC or on short final to a controlled airport such an indication is extremely useful to the controllers.

- 7500 indicates hijack.

When a controller's secondary radar detects any of these codes, it highlights the echo and, should the transponder descend below the radar's line of sight, the last known position of the transponder is stored.

11.9.5 Survival—Basic Techniques

The basic techniques of survival while waiting for Search and Rescue have filled many books. *Down but not Out*, issued by the Canadian Department of National Defence (Publication B-GA-217-001/PT-001) is written for pilots (albeit military ones)[16] and contains much valuable information. It is currently out of print but copies can be obtained from online and physical second-hand bookshops. This book identifies the primary enemies of survival:

1. Pain—once given in to, pain will weaken the drive to survive.
2. Cold—an insidious enemy that lowers your ability to think.
3. Thirst—even when not extreme, it can dull the mind.
4. Hunger—another factor that can lessen the ability to think rationally.
5. Fatigue—something that can make a person careless and deflect him or her away from the goal of survival.
6. Boredom and Loneliness—the two toughest (and often unexpected) enemies of survival.

The book contains practical advice ranging from the construction of shelters to first-aid and ways of finding food. It should be in every aircraft that flies across open countryside, along with emergency food supplies, first aid kits, tents, etc.

One of the primary indirect causes of injury after a forced landing is complacency before takeoff.

Anecdote 41 *I know an experienced pilot injured by frost-bite after a crash in winter who was wearing inadequate clothing "because the flight was not going further than 5 miles from the airport". I also know another pilot who was forced to land on a frozen lake following an engine failure and who, having fallen through the ice and soaked his clothes, survived until rescue arrived by wrapping himself in the aircraft's insulating engine cover.*

In a Canadian winter, a crash even 5 miles from an airport could easily leave a pilot in $-20°C$ for thirty minutes. Always have warm clothing and a survival kit on board and make the best use of other insulating material such as an engine cover.

[16] It also refers to all pilots as "he", something that gives it a period flavour.

Section 602.61 of the CARs states that, with a few exceptions such as gliders and balloons:

> no person shall operate an aircraft over land unless there is carried on board survival equipment, sufficient for the survival on the ground of each person on board, given the geographical area, the season of the year and anticipated seasonal climatic variations, that provides the means for
>
> - starting a fire;
> - providing shelter;
> - providing or purifying water; and
> - visually signalling distress.

11.10 Answers to Exercises

Exercise 87

Approach lighting for runway 09 is of type AJ (centre row, low intensity) and AS (uni-directional flashing strobe lights at the runway threshold). There are medium intensity runway edge lights (ME) and green/red threshold lights (TE). Glideslope guidance is given by a VASIS of type V1 (suitable for aircraft with EWH of up to 3 metres). The lighting for runway 27 is the same.

Exercise 88

Hydroplaning is possible at any speed above $9 \times \sqrt{25} = 9 \times 5 = 45$ knots.

Exercise 89

Using an aviation calculator, the answer is easily found as being 2,692 ft—on this particular day, to the aircraft rolling down the runway, Houston aerodrome appears to be at 2,692 ft above sea level.

If an aviation calculator is not available, then the pressure altitude can be estimated by calculating the difference between the altimeter setting and 29.92 and multiplying this difference by 1000 to get feet. In this case $29.92 - 29.34 = 0.58$. Thus the pressure altitude differs from the true altitude by $0.58 \times 1000 = 580$ ft. Since the pressure is lower than standard, the airport appears to be higher than it actually is—at $2150 + 580 = 2730$ ft. This is 48 ft different from the more exact figure given by the calculator.

Exercise 90

Using an aviation calculator, it is easy to find that the density altitude is 4,452 ft. Thus, on this day, as far as the aircraft rolling down the runway is concerned, Houston is at 4,452 ft above sea level.

Exercise 91

There are various methods for performing this calculation:

- With an aviation calculator, the headwind is immediately given as 19 knots and the crosswind as 11 knots.
- Using the chart given in the AIM or CFS the crosswind is found to be approximately 11 knots and the headwind approximately 19 knots. The technique is as follows (see figure 11.20):
  - Calculate the angle by which the wind will be off the runway centreline: $320° - 290° = 30°$.
  - Draw a dot on the chart on the 30° radial at a distance of 22 knots (use the quarter circles as reference).
  - Draw horizontal and vertical lines from the dot to the two axes and read off the headwind and crosswind components.
- Using simple trigonometry (not required for the Transport Canada examination), the components can be calculated as:

$$\begin{aligned} \text{crosswind} &= 22 \times \sin(320° - 290°) \approx 11 \text{ kts} \\ \text{headwind} &= 22 \times \cos(320° - 290°) \approx 19 \text{ kts} \end{aligned}$$

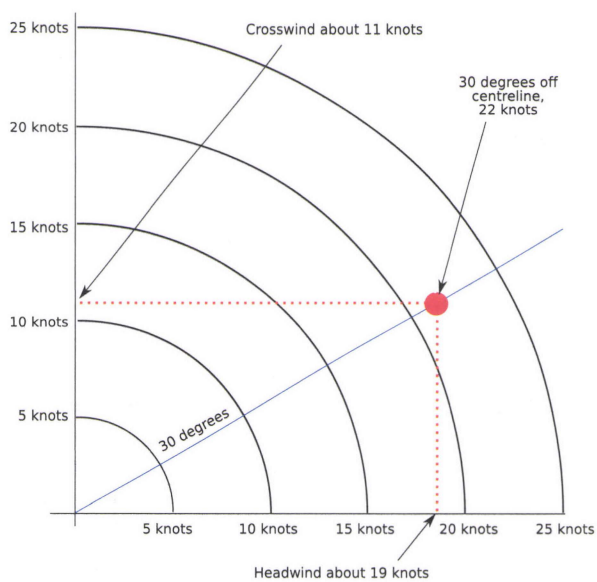

Figure 11.20: Crosswind Chart for Exercise 91

Exam Hint 28 *If you have to use a chart like that of figure 11.20 in an examination, and can't remember which axis gives the crosswind and which the headwind, then pretend the wind is straight down the runway (0° from the centreline). Then there is no crosswind and all the wind is headwind—the headwind is therefore given by the horizontal axis.*

Exercise 92

Figure 11.21 illustrates the process used:

1. Start at the temperature (20°C) and go straight up to the pressure altitude curve (indicated by a dot).
2. Move horizontally to the dotted reference line.
3. Using the guidelines, move to the weight (1800 lbs) and then move horizontally to the next dotted reference line.
4. Use the guidelines to move to a tailwind of 5 knots and then move horizontally to the takeoff distance.

This path is traced on figure 11.21 with a heavy dotted line. The takeoff distance can be read off the chart as being about 2,150 ft.

Exercise 93

- **Step 1: Calculate the Pressure Altitude.**
  Using an aviation calculator, the pressure altitude is found to be 1,467 ft. If a calculator is not available, then an estimate can be made by assuming that each inch of mercury above or below 29.92″ represents 1,000 ft. Using this approximation, the pressure altitude would be estimated as
  $1000 + ((29.92 - 29.42) \times 1000) = 1500$ ft,
  a difference of 33 ft.
- **Step 2: Consult the Table in the POH (Section 5)**
  There is no row for 1,467 ft pressure altitude in the takeoff distance table in the POH and there is no column for a temperature of 18°C in the table. At this point you have two options: be safe and assume a pressure altitude of 2,000 ft and a temperature of 20°C (which would give you distances of 1,075 ft and 1,895 ft) or you can interpolate the figures. Firstly, draw up a table of what you know:

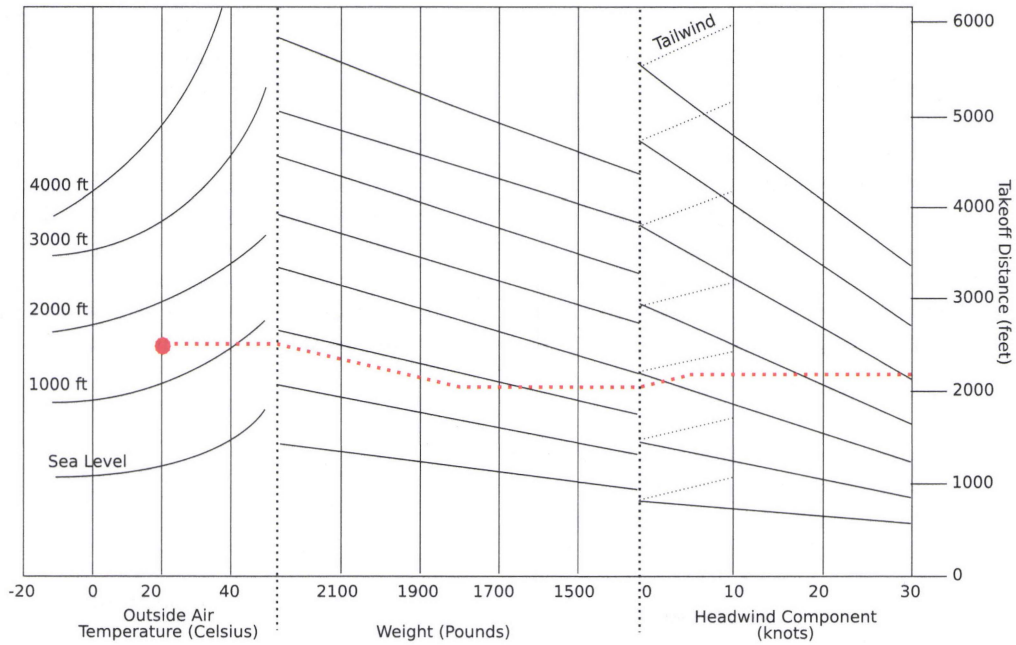

Figure 11.21: Solution to Example 92

	10°C	18°C	20°C
1000	915/1615		980/1725
1467			
2000	1000/1770		1075/1895

The numbers for 1,467 ft and 18° have not been filled in because we don't know them (yet). Consider the 10°C column: 1,467 ft lies 46.7% of the way between 1,000 ft and 2,000 ft, so the ground-roll distance should lie 46.7% of the way between 915 ft and 1,000 ft, i.e., 955 ft. We can similarly calculate the 1,467 ft values in the 20°C column to get:

	10°C	18°C	20°C
1000	915/1615		980/1725
1467	955/1689		1025/1806
2000	1000/1770		1075/1895

This assumes that the relationship between the takeoff distance and pressure altitude is linear (i.e., a straight line). In the absence of other information and given the small differences being considered here (e.g., a difference of $1000 - 915 = 85$ ft in the ground roll figure), this is reasonable.

We still don't have anything in the 18° column. 18° lies 80% of the way between 10° and 20° so the ground roll at 1,467 ft Pressure Altitude will be 80% of the distance from 955 to 1,025 ft. The difference between 955 and 1,025 ft is 70 ft and 80% of this is 56 ft. The ground roll is therefore $955 + 56 = 1011$ ft. The other value can be calculated similarly, giving this table:

	10°C	18°C	20°C
1000	915/1615		980/1725
1467	955/1689	1011/1775	1025/1806
2000	1000/1770		1075/1895

This is what we wanted to know: interpolation has effectively added a row and a column to Cessna's table. After all our hard work, the difference between the exact number for the ground roll (1,011 ft) and the number we estimated by assuming 20° and 2,000 ft (1,075 ft) is only 64 ft! In an examination, do the hard work unless only one of the multiple-choice answers is reasonable. Outside the examination room, use the more pessimistic figure, as the numbers are determined for a new aircraft with a perfect pilot—conditions not found with every takeoff.

- **Step 3: Apply Correction for Wind**

There is a 23 knot wind 290° - 270° = 20° degrees off the runway centreline. Using the technique described in section 11.5.1, this can be resolved into a 22 knot headwind and an 8 knot crosswind component. The Cessna table indicates that distances can be reduced by 10% for every 9 knots of headwind. As we have 2.44 × 9 knots of headwind, we can reduce both figures by 24.4%. Ground roll is therefore 1011 x 0.756 = 764 ft and the distance to clear a 50 ft obstacle is 1775 x 0.756 = 1342 ft.

- **Step 4: Apply Correction for Grass Runway**

  The runway is grass so, according to the table in the POH, we are required to add 15% of the ground roll figure to both the ground roll and the distance to clear a 50' obstacle. 15% of 764 ft is 115 ft so we must add this to both figures calculated above. The revised ground roll is therefore 764 + 115 = 879 ft and the distance to clear the obstacle is 1342 + 115 = 1457 ft.

Answer: Ground Roll of 879 ft and Distance to Clear 50 ft Obstacle of 1,457 ft.

Exercise 94

Ignoring for a moment the temperature being above standard, it can be seen that climbing from sea level to 8,000 ft pressure altitude would take 18 minutes, during which time the aircraft would consume 3.3 gallons of fuel and cover 23 nautical miles. However, the aircraft is departing from an aerodrome already at 3,000 ft pressure altitude and so the equivalent numbers for climbing from sea level to 3,000 ft (5 minutes, 1.1 gallons and 7 nautical miles) can be subtracted from these figures. This means that at standard temperature, to climb from 3,000 to 8,000 ft pressure altitude, the aircraft would need 13 minutes, 2.2 gallons of fuel and cover 16 nautical miles. *Note that this is not the same as a 5,000 ft climb from sea level.* The temperature is 10Cdeg above standard and so, in accordance with the note, 10% must be added to each of the three figures. The required values are therefore 14.3 minutes, 2.42 gallons of fuel and 17.6 nautical miles.

Exercise 95

Applying equation 11.1:

$$\text{additional drag} = w \times \sin(\theta) = 2300 \times \sin(3°) \approx 120.3$$

So the Cessna 172 experiences an additional 120 lbs-force of drag during its takeoff run. Given that the approximate maximum thrust of a Cessna 172 with an O-320 engine is about 470 pounds-force, this represents a loss of about 25% of the total power. This is not insignificant.

Exercise 96

As the King Air has 13 passenger seats, the penultimate row of figure 11.14 must be used—the table row depends not on how many passengers there are on board, but on how many seats the aircraft has. January is a winter month in Canada and so the total assumed weight will be

$$(5 \times 196) + (3 \times 233) = 1679$$

A total weight of 1,679 lbs must therefore be assumed.

Exercise 97

This is a simple application of equation 11.2:

$$\frac{\text{weight moved} \times \text{dist moved}}{\text{aircraft weight}} = \frac{55 \times (123 - 73)}{2134} \approx 1.3$$

So the centre of gravity will move forward 1.3 inches.

Exercise 98

The CRFI value of 0.27 lies between the values 0.30 and 0.25 given in the table. For a Transport Canada examination it might be necessary to perform a linear interpolation. Using the "thinking" method described in appendix D.3 on page 349:

- The difference between the two CRFIs is $0.30 - 0.25 = 0.05$.
- The difference between the two landing distances is $5080 - 4750 = 330$ ft.
- 0.27 is 60% of the way from 0.30 towards 0.25.
- 60% of 330 ft is 198 ft.
- The answer is therefore 198 ft more than 4,750 ft, i.e., 4,948 ft.

The actual distance given by Transport Canada when the CRFI is 0.27 is 4,940 ft, an error of 8 ft in our calculated answer.

Chapter 12

Airframes & Engines

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A basic knowledge of engines and airframes can be of inestimable use to any type of pilot. Even though it is unlikely that you will be designing an engine or airframe from scratch, an understanding will provide you with the confidence to assess the importance of any changes you notice in your engine and airframe. Your gauges show that one cylinder has suddenly become slightly cooler than the others; does it matter? You normally use 15W50 oil but the aerodrome where you are currently parked only has 20W50 available; may you mix this with your existing oil? When performing the magneto checks after landing you find that there is no drop in rpm when you ground the left magneto; precisely what does this mean?

12.1 Airframes

12.1.1 Types of Construction

There are two main considerations for the construction of airframes:

1. Should the skin of the airframe be load-bearing or should the load be carried by internal frames?

2. From what material should the airframe be built?

Airframe Rigidity

The first aircraft had airframes made of wood or steel tubing covered with fabric to create a smooth and lightweight surface. *Madapolam*, a soft, cotton fabric, was a common covering material, woven in such a way as to absorb fluids equally in both major directions, thus allowing it to be tautened and stiffened with dope. Once doped, such a covering could provide a little strength in tension (i.e., when pulled) but none in compression (when pushed from its ends)—almost all of the strength of the airframe had to be provided by the internal frames. Airframes constructed in this way are known as *truss-type* airframes. The truss-type fuselage of a Steen Skybolt is shown under construction in figure 12.1.[1]

Even early aircraft were generally not fully truss-type: designers began to incorporate sheet metal or plywood to the most highly stressed parts of the internal frames, moving some of the structural load to the skin of the aircraft. An airframe where the skin takes the whole structural load is known as *monocoque*[2] (or *structural skin*). A good example of a monocoque structure is a chicken's egg: the shell of the egg provides strength and rigidity while being itself light.

[1] Other photographs at `http://www.steenaero.com/Skybolt`.
[2] From the French for single (mono) and shell (coque).

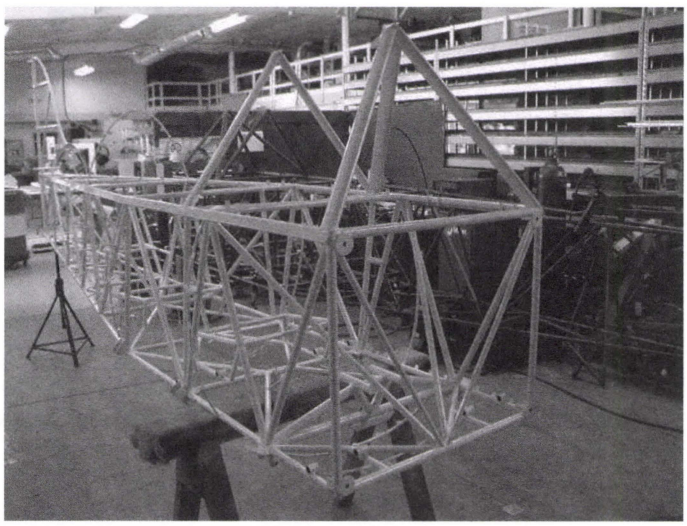

Figure 12.1: A Truss-Type Fuselage under Construction

The first true monocoque fuselage was probably that created by the Frenchman Louis Béchereau for the Deperdussin Monocoque racing aircraft in 1912.[3] Since the cost of aluminium was so high, its fuselage, which provided both the external skin and its load bearing structure, was made of plywood—see figure 12.2.

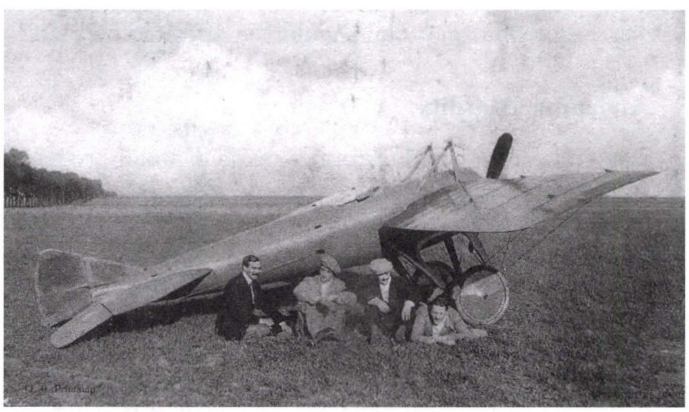

Figure 12.2: The Deperdussin Monocoque

Designers realised that a thick metal skin could eliminate the need for any internal framing, but its weight would be prohibitive. Thin sheet metal, on the other hand, while light enough, buckles under bending and compression. This led to Junkers developing the idea of corrugating a thin metal skin to give it better compression properties. In the mid 1920s, the concept was used on the Ford Tri-Motor and Ford had to defend itself against patent challenges from Junkers. While the corrugation did not completely eliminate the need for an internal frame, it did lighten that frame significantly.

During the late 1930s, Barnes Wallace used his success with the frames of airships (e.g., the R100) to design a so-called *geodetic* (sometimes also known as *geodesic*) airframe for Vickers. This type of construction, using pliable, flat strips of wood bent about formers in opposite spiral directions, was light, strong and rigid and was used for the Wellesley and Wellington bombers. Strictly speaking this was a truss-type fuselage (with a fabric covering) but it evolved naturally into a monocoque construction for aircraft such as the de Havilland Mosquito.

An inadequate understanding of metal monocoque design resulted in catastrophic explosive decompressions of several pressurised airframes, including the 1954 de Havilland Comet disasters. The investigations following these found that the Comets' fuselage failures were caused by a poor understanding of how stresses are distributed around openings (e.g., windows and antennæ) in a stressed skin, and an inadequate understanding of the propagation of cracks caused by metal fatigue. The lessons learned from the Comet were incorporated into the design of the Boeing 707 and later airliners.

In June 2018 the head of Emirates said that the airline intends to remove all windows from the passenger compartments of its Boeing 777s, replacing these with high-definition video screens displaying the outside view. He claims that removing the windows and the associated metalwork to handle stress, will reduce the weight of the aircraft by 50%, thereby saving substantially on fuel. This would also eliminate the risk of windows fracturing and causing depressurisation.

Most modern aircraft have monocoque or semi-monocoque airframes, although sports and aerobatic aircraft still use truss-type airframes extensively (as in figure 12.1).

Airframe Materials

Early aircraft were built primarily of wood because, aluminium, the main ingredient of Duralumin, the alloy from which modern aircraft are largely built, was prohibitively expensive. From the late 1920s, as aluminium became cheaper, it replaced wood both for the internal frames and the external skins of aircraft.

Increasingly, polymer/fibre-reinforced composite materials are being used for the structural components of airframes. These materials were introduced in the 1930s for non-load-bearing structures such as fairings (plates added to smooth the airflow over the airframe), radomes (covers for antennæ and other equipment outside the airframe), etc. The first complete fuselage built from composites is believed to be a test Supermarine Spitfire made in the early 1940s by Aero Research Ltd. in Duxford, England. The use of composites for production aircraft really only became possible when

[3] It held the world airspeed record of 203 km/hr in 1913.

ultra-high-strength Boron, Carbon and Aramid fibres were introduced in the late 1960s and early 1970s.

Today's commercial airliners and general aviation aircraft have airframes made in whole or part from composite materials. The A380 Airbus, for example, has a carbon-fibre composite centre section wing box. This structure is the largest single component in the aircraft, measuring 7 × 6 × 2 metres cubed, with a mass of 4,500 kg.

The Boeing 787 Dreamliner is the first commercial airliner to be constructed entirely of composite materials (with a few exceptions on the engine pylons, heated leading edges, etc.).

In spite of the long history of composite construction, some aspects of its use are still not fully understood. Composite structures do not react like metals to normal wear and tear, and they do not display any of the typical signs of damage (dents, cracks, corrosion, creep, etc.) that alert a mechanic to problems in a metal airframe. The loss of an Airbus A300-600R over Jamaica Bay, New York, USA in October 2001 was the result of a catastrophic failure and separation of the all-composite vertical stabilizer.

12.1.2 Landing Gear

Types of Landing Gear

The landing gear on an aircraft is designed not only to support it as it moves on the ground but also to handle the large stresses that occur during landing.

This section deals exclusively with wheeled landing gear; floats and skis are not considered. Wheeled landing gear comes in two types:

1. *conventional* or *taildragger* where the main wheels are forward of the aircraft's centre of gravity and the third wheel or skid is close to the tail. Because the centre of gravity lies behind the main wheels, taildraggers are harder to land in crosswinds because any sideways motion is likely to lead to a ground loop (i.e., the aircraft turning around on the runway). The primary advantage of a taildragger is that it can land on fields rougher than those accessible to tricycle gear aircraft.

2. *tricycle* where the main wheels are behind the aircraft's centre of gravity and the third wheel is at the nose.

Most modern aircraft have tricycle landing gear although sometimes a small tail wheel or skid is added to guard against tail strikes during takeoff: for example, the Concorde had a retractable tail "bumper" wheel because aircraft with delta wings rotate to a large angle when taking off. The Boeing 727 also had a retractable tail bumper.

The other major feature of landing gear is whether or not it retracts in flight: almost all large aircraft have retractable wheels to reduce parasitic drag (see section 9.5.4 on page 181). The Frenchmen Alphonse Pénaud and Paul Gauchot were the first people to design a retractable landing gear—in 1876 they included retractable landing gear on the design of their steam-powered, amphibious monoplane.[4] Actual implementation of retractable landing gear did not appear until 1917.

Steering

When travelling on the ground, the landing gear is used to steer the aircraft: by turning the nose (tricycle) or tail (tail dragger, conventional) wheel and by the use of differential braking. On some multi-engine aircraft and at some speeds, steering with the landing gear is augmented by the use of differential power.

Anecdote 42 *In many light aircraft the brake pads on the main wheels are exposed to the elements. It is common for a pilot to add too much power during taxiing before flight and "ride the brakes". This can heat the brake pads and, in the winter, melt any snow or ice on them. Unfortunately, once in the air the water refreezes and is ready to trap an unwary pilot on landing.*

This happened to me when I was with a student and luckily we were landing on an ice-covered runway without a crosswind. This meant that we were approaching at the minimum safe airspeed and the locked left wheel did not cause an immediate problem. Some fancy footwork was, however, required to keep the aircraft on the runway and, once we had stopped, we had to radio for a tow-truck to get us onto the taxiway.

Landing Gear Retraction Mechanisms

Retraction and lowering of landing gear is normally powered by hydraulic systems (see section 13.5.2 on page 300) or by geared electrical motors driving a screw jack. Lights on the instrument panel allow the pilot to verify whether or not the landing gear is locked down.

Landing Gear Incidents

Malfunctions of retractable landing gear or human errors in not lowering it before landing have been the cause of

[4] This design met with such derision from their contemporaries that Pénaud committed suicide in 1880.

many accidents: there are approximately 100 occurrences of an aircraft landing with its gear up each year in the USA. For the transcript of a DC-9 landing without lowering its wheels, see appendix B.2 on page 342.

12.2 Creating Thrust

There are many types of engines used to power aircraft, including rockets, jets, Wankel rotary engines, electric motors and two- and four-stroke piston engines. This book, following Transport Canada's syllabus, concentrates on two main types: the four-stroke gasoline engine and the turbine (jet) engine. Additionally, some information is given about two-stroke engines (section 12.4.3), diesel engines (section 12.4.4) and electric motors (section 12.5).

Jet engines create thrust in the same way as reciprocating engines with propellers: they move a mass of air backwards and, by Newton's Third Law of Motion (see section 9.2.4 on page 167), this causes the aircraft to move forwards.[5] Contrary to some popular belief, the jet engine does *not* work by forcing expelled air against the outside atmosphere. In fact, if a suitable source of intake air could be provided, a jet engine would work in a vacuum (as does a rocket, a form of jet engine).

Reciprocating and jet engines are also similar in their method of operation: they both suck in air (or an air/fuel mixture), compress that air, burn fuel to cause the air to expand and allow the resulting mixture to escape as exhaust. The primary difference between the two types of engine is that, in a cylinder of a reciprocating engine the four stages take place one after the other; in a turbine engine all four stages take place simultaneously in different parts of the engine.

The simplicity of a turbine engine gives it a greater reliability than a reciprocating engine and, at cruise speeds above 400 knots, a jet engine is more efficient than a propeller. For aircraft that cruise below that speed a turboprop is used; a turbine engine turns a propeller instead of acting as a pure jet.

12.3 Turbine Engines

12.3.1 Jets: Principle of Operation

There are three basic types of jet engine: ram jet, pulse jet and gas turbine.[6] These all work on the same principle, forcing air backwards to cause a forward thrust, but differ in their mechanism.

[5] In the same way that a canoeist forces water backwards, and this moves the canoe forwards.

[6] A rocket can also be considered a form of jet engine.

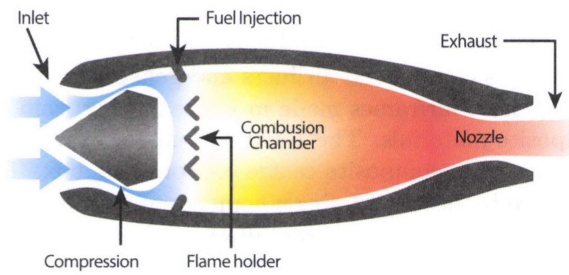

Figure 12.3: A Ram Jet

A **Ram Jet** has no moving parts at all, working by the shape of its ducting; see figure 12.3. As the jet moves through the air, air enters the front of the jet into a duct where the cross-sectional area is increasing—the opposite of a venturi. By Bernoulli's principle, its pressure will increase. Fuel is then burned to increase its pressure still further and the expanding gases are forced out of the outlet, causing the jet to move forward. As this description indicates, there is one characteristic of the ram jet that makes it unsuitable for use in aircraft—it only works if it is already moving forward at a significant speed, being most efficient at speeds of approximately Mach 2. Its use is therefore restricted to missiles and other military applications.

A **Pulse Jet** A pulse jet has a duct similar to that of the ram jet but the incoming air passes through a number of valves; see figure 12.4. Fuel is then injected and burned, increasing the pressure in the combustion chamber, forcing the valves shut and preventing any more air from entering. The expanding gases then force their way out of the rear of the engine, propelling the aircraft forward. The fuel flow is then stopped, the valves open and the process is repeated. The pulse jet differs from both the ram jet and the gas turbine in that the combustion process is not continuous—instead being pulsed.

Pulse jets have a long history, the first working system being patented in 1906 by the Russian engineer V.V.Karavodin. Because of the vibration and noise they cause, their use is limited today to pilotless drones and model aircraft.

A **Gas Turbine** is the only type of jet engine considered further in this book.

12.3.2 Turbojet Engines

The basic operation of a gas turbine engine is illustrated in figure 12.5. The only rotating part is a single shaft connecting the compressor blades at the front of the

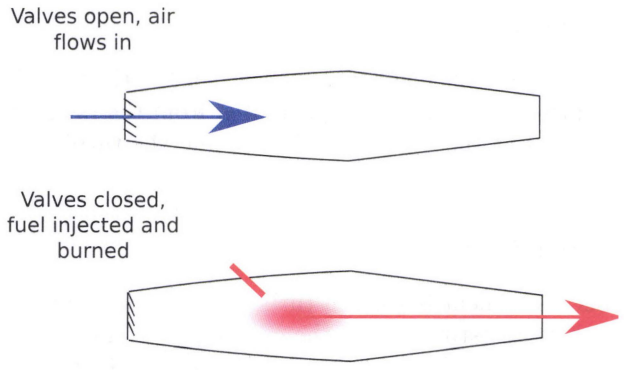

Figure 12.4: The Principle of the Pulse Jet

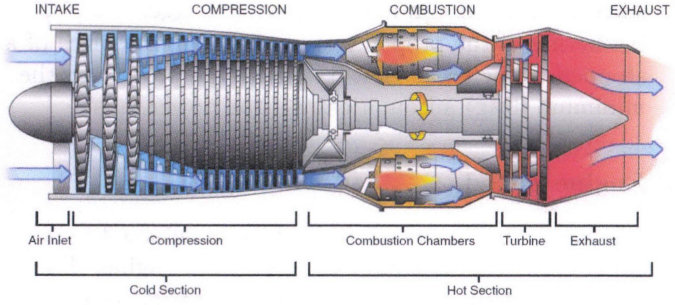

Figure 12.5: A Simple Turbojet (FAA)

engine with the turbine at the back. Imagine that this is already turning, then:

- air is sucked into the front of the engine by the rotating compressor and pushed in by the movement of the aircraft through the air.
- air moves through the compressor blades and is compressed.
- in the combustion chamber fuel is burned and this heats the air, causing it to expand.
- the expanding air passes through the turbine, causing it (and therefore the compressor) to turn.
- the hot air is expelled from the rear of the engine.

By this means air is taken in, accelerated and expelled to the rear. By Newton's Third Law, the engine therefore experiences a thrust forward. The amount of thrust is set by controlling the amount of fuel injected into the combustion chambers. To create more thrust, the pressure of the fuel applied to the spray nozzles is increased.

This explanation presupposes that the engine is already turning. Without expanding air flowing through the turbine, the compressor will not turn and no air will be sucked in. To start a turbine engine:

1. the compressor/turbine shaft must be set turning. This is typically achieved on commercial (non-military) aircraft by means of a starter turbine, powered by compressed air from an external source—an Auxiliary Power Unit (APU). The rotating starter turbine drives the main shaft through a system of gears.
2. fuel must be injected into the combustion chambers and ignited. An electrical ignition system discharges across an igniter plug to create the spark—see section 13.2.2 on page 291.

Once the engine is turning under its own power, the starter turbine can be disengaged and the ignition plug extinguished. In some flight conditions, however, the ignition system is kept running continuously at a lower power level to prevent a "flame-out", e.g., when taking off into heavy rain or flying in icing conditions.

In the same way that a conventional reciprocating engine is affected by the reduced air density as the aircraft climbs (see section 12.4.10), so is a turbine engine. In both types of engine the amount of fuel must be adjusted to match the reduced density of the air. In a reciprocating engine, this is performed with the mixture control; in a turbine an automated system reads the current engine condition (exhaust gas temperature, air intake pressure, etc.) and controls the fuel pump.

12.3.3 Turbofan Engines

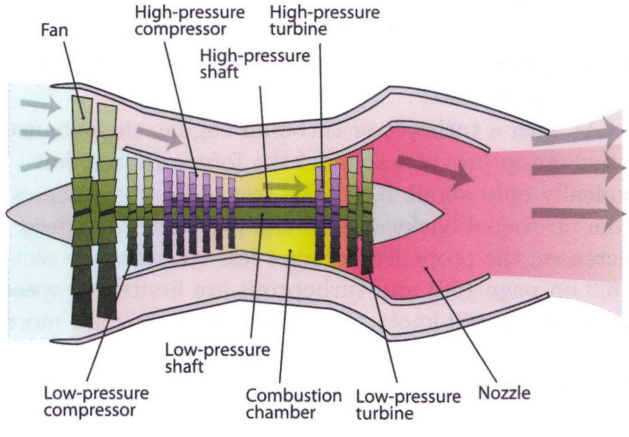

Figure 12.6: A Low Bypass Turbofan (K. Aainsqatsi)

In the engine shown in figure 12.5, all of the compressed air is passed to the combustion chambers. This is characteristic of a turbojet (a "zero-bypass" engine), but in most turbine engines some of the incoming air bypasses the combustion chambers, being driven by a fan at the air intake. Such engines are called turbofans; see figure 12.6.

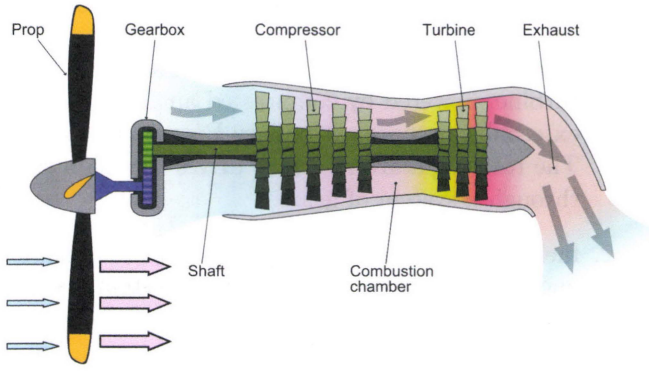

Figure 12.7: A Turboprop Engine (Emoscopes)

The bypass ratio (BPR) of a turbofan is the ratio of the mass of air flowing through the bypass to the mass of air flowing through the combustion chamber. A 5:1 BPR, for example, as is used in the engines on the Airbus A330, means that 5 kg of air passes through the bypass for every 1 kg of air that passes through the core. On the engines of commercial airliners, bypass ratios are typically between 3:1 and 10:1.

12.3.4 Turboprop Engines

There is a limit on the size of the fan that can be used in a turbofan engine as the tips of the fan must not become super-sonic. A turboprop engine can be seen as an extension of a turbofan engine, where the "fan" becomes an external propeller with a gearbox to reduce its rotational speed; see figure 12.7. A turboprop engine can be thought of as a special type of turbofan with a very large bypass ratio.

As with a turbojet or turbofan engine, the exhaust of a turboprop provides some of the forward force, but typically only about 10%. The rest of the force comes from air forced backwards by the propeller. As speed increases, the propeller becomes less efficient (see section 9.6.3 on page 190) and turboprops are limited to speeds below about 400 knots. At these speeds they are more fuel-efficient than turbofans, but have a lower ceiling (i.e., cannot cruise as high).

12.3.5 Turbine Instrumentation

Engine instruments in modern turbine aircraft are displayed on an electronic screen. Generally only the instruments required for the crew to monitor and set the engine thrust are displayed, the other instruments appearing only when their readings are anomalous.

Engine Thrust

This instrument displays a measure of the thrust being produced by each engine, generated from the ratio of the pressures at the compressor intake and the turbine discharge.

Engine Torque

This instrument is used in turboprop aircraft and displays an estimation of the engine power (in horsepower or Watts). The amount of torque[7] being created is taken from a transducer[8] measuring the oil pressure produced by the rotating propeller shaft. The same transducer can also be used to trigger the feathering of the propeller (i.e., changing the pitch of a stopped propeller so that its blades are producing the minimum drag) automatically if the power fails.

Engine Speed

The rotational speed of the turbine is detected by a small electrical alternator driven by the engine. The frequency of the generated electrical current is a measure of the speed of rotation and this is displayed for the pilot.

Turbine Gas Temperatures

Thermocouples are used to measure the temperature of the gases leaving the turbine (known as the *Exhaust Gas Temperature, EGT*) and are used to present the pilot with an indication of the correct operation of the engine, in particular to detect a temperature exceeding the maximum allowed value.

Oil Temperature & Pressure

As with a reciprocating engine (see *Oil Pressure* on page 275), awareness of the lubricating oil temperature and pressure is essential for the correct operation of a turbine engine.

Fuel Temperature & Pressure

The temperature and pressure of the fuel are measured to ensure that the fuel flowing into the combustion chambers is not at so low a pressure compared with the pressure in the chamber that vapour bubbles can form in it (so-called *cavitation*) and that the temperature of the fuel is suitable for the operational conditions.

[7] *Torque* is a measure of how much a force is tending to turn something—in this case the shaft.

[8] A *transducer* is a device that responds in a predictable and measurable way to something: temperature, pressure, etc.

Fuel Flow

The rate of fuel flow to an engine gives not only a method of estimating the amount of fuel consumed (and therefore the amount of fuel remaining) but is also a sensitive indication of the health of the engine.

Vibration

Unlike a reciprocating engine, a turbine creates very little vibration. Any vibration that does occur is likely to be an indication of an impending failure. Many turbine engines are therefore fitted with a transducer that measures vibration and transmits its readings to the computers monitoring the engines and to the pilot.

12.3.6 Full Authority Digital Engine Control (FADEC)

FADEC variously stands for *Full Authority Digital Engine Control* and *Full Authority Digital Electronics Control* and is a computer-based system available for both turbine and reciprocating engines.

A FADEC system receives inputs from various sensors monitoring the current flight and engine conditions, typically including air density, throttle position, engine temperatures and cylinder pressures. The computer in the FADEC system then computes the optimal fuel flow, mixture ratio, bleed valve position, etc. and sets these without pilot intervention. It also logs information for a mechanic or the engine's manufacturer.

For piston-engines, the FADEC system eliminates the need for magnetos, carburetor heat, mixture controls and engine priming, thereby reducing maintenance and fuel costs. It can also adjust the mixture individually for each cylinder—something that is not possible with a single, manual mixture control.

One disadvantage of FADEC systems is their failure modes—if a FADEC unit or its electrical power feed fails, then the engine stops. In contrast, one major advantage of the magneto system (see page 289) is that it is self-contained: there is no requirement for external electrical powering. To reduce the chances of engine failure, aircraft fitted with FADEC systems have duplicated electrical power systems, including duplicated batteries.

Most (but not all) FADEC systems provide manual override but, even when this exists, accidents have occurred: see, for example, the USA National Transportation Safety Board recommendation issued on 15th December 2004. In the incident being analysed, the FADEC system on a Bell 407 helicopter failed and the pilot reacted too quickly. The system required the pilot to wait 6 seconds after engine failure (!) to give the FADEC system time to switch to manual operation. By reacting too quickly, the pilot had prevented the FADEC system from switching itself off.

12.3.7 Fuels

There are three main grades of turbine fuel used in non-military turbine aircraft: Jet A-1, Jet A and Jet B:

JET A-1. This is a form of kerosene used in most turbine engined aircraft. It is produced to an international standard, has a flash point[9] above 38°C and a freezing point no higher than −47°C. JET A-1 is sometimes known as AVTUR.

JET A. Jet A is also a form of kerosene. It has the same flash point as Jet A-1, but a higher maximum freezing point of −40°C. JET-A is only available in the USA.

JET B. Jet B contains both naphtha and kerosene and is used as an alternative to Jet A-1 in very cold weather. It is more difficult to handle because of its higher flammability.

Jet fuel is very similar to diesel, and some aircraft engine manufacturers offer piston engines that run on jet fuel. If these become popular then they could address the issues associated with the possible phasing out of leaded avgas for environmental as well as supply reasons.

Unlike AVGAS, jet fuel is not dyed; it is clear or straw coloured.

12.3.8 Further Reading

The Rolls-Royce book *The Jet Engine*, originally published in 1986 and republished in 2005, is an excellent and thorough introduction to turbine engines. Both its diagrams and its textual explanations are carefully written to be accessible to a beginner while being sufficiently accurate to satisfy an expert. It is available from the Rolls Royce website or from the normal online bookshops.

12.4 Reciprocating Engines

Reciprocating engines are so-called because the pistons reciprocate in the cylinders; one of the meanings of the word "reciprocate" given in dictionary.com is "to move alternately backward and forward." The basic motion of a turbine engine is rotation; the basic motion of a reciprocating engine is backwards and forwards in the cylinder. To turn a propeller, the reciprocating motion has to be turned into a rotation.

[9] The flash point of a liquid is the lowest temperature at which it can form an ignitable mixture in air.

12.4.1 Engine Operation

The basic concept of the reciprocating engine, whether gasoline or diesel, and whether two- or four-stroke, is to make a piston move repeatedly from one end of a cylinder to the other. The means by which the piston is made to move are described in the sections below. Figure 12.8 shows a cylinder from a Wright J-4B engine cut away to expose the piston and valves.

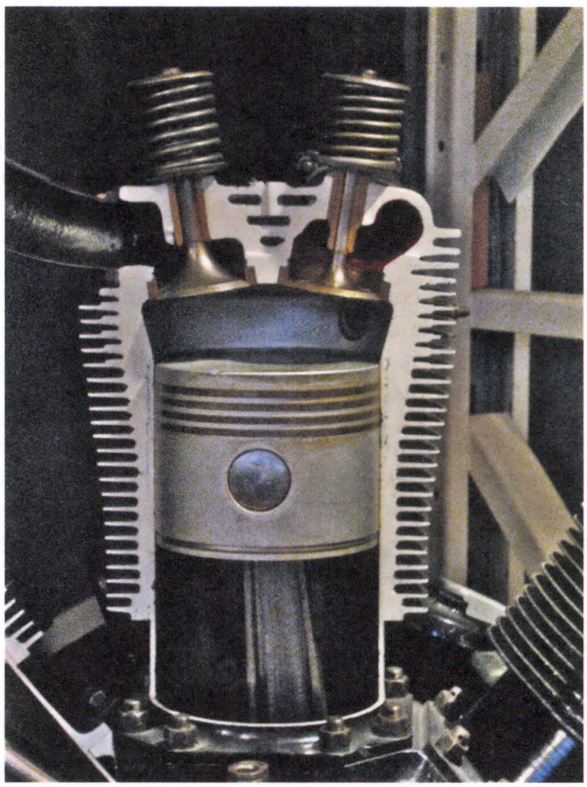

Figure 12.8: A Piston in its Cylinder (Jenny Lewis)

The internal diameter of the cylinder varies from engine to engine but, as an example, that of a Teledyne Continental cylinder for an O-300 engine is about 103 mm. The piston fits into the cylinder with a clearance of about 0.23 mm.

Reciprocating motion by itself is not useful because a propeller-driven aircraft requires rotary motion for the propeller. The basic principle of the conversion for a single cylinder is illustrated in figure 12.9: the oscillatory motion of the piston in the cylinder is translated into rotary motion through a "connecting rod" joining the piston to an off-centre point on a fly-wheel.

In a practical engine there is more than one cylinder and the output from all the cylinders needs to be combined. This is done as illustrated in figure 12.10 where the connecting rods are joined to several off-centre devices connected to the same rotating axle: the "crankshaft". As can be seen in that figure, the different

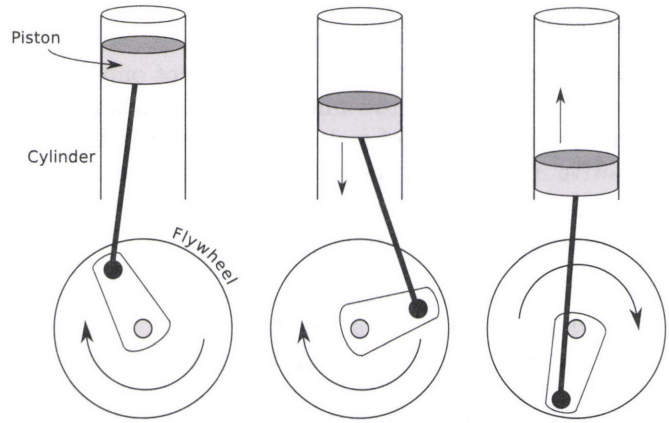

Figure 12.9: Converting Reciprocating to Rotary Motion

pistons (four in this case) will, at any time, be at different points in their cylinders: some going up and some down.[10]

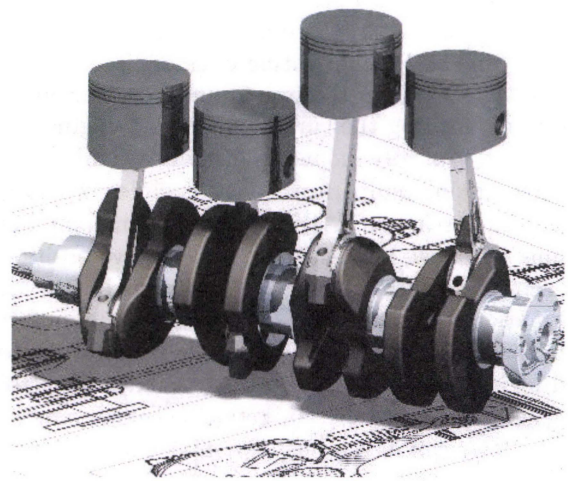

Figure 12.10: Connecting the Pistons (FreeFormer)

12.4.2 The Four Stroke Cycle

The first patent for a four-stroke engine was taken out by Eugenio Barsanti and Felice Matteucci in 1854, but the first practical engine of this type was constructed in 1876 by the Germans Nicolaus Otto, Gottlieb Daimler and Wilhelm Maybach. The four-stroke cycle is often known as the *Otto Cycle* in honour of Nicolaus Otto's work.

The four strokes are illustrated in figure 12.11 and relate to a piston moving within a cylinder and are:

Induction (or Intake) Stroke. During this stroke the exhaust valve is closed, the intake valve is open

[10] The terminology "up" and "down" is used even in engines where the cylinders are mounted horizontally: "up" means away from the crankshaft.

and the piston is drawn downwards by the rotating crankshaft.[11] As the piston descends it sucks a fuel/air mixture from the carburetor into the cylinder.

Compression Stroke. During this stroke both valves are closed and the piston moves upwards in the cylinder, being driven by the inertia of the crankshaft and a power stroke from another cylinder. This compresses the fuel/air mixture.

Power Stroke. Just before the piston reaches the top of its travel during the compression stroke, the spark plugs fire, igniting the fuel/air mixture. This is timed so that the burning of the fuel moves across the cylinder and starts to create downward pressure on the piston just after it has reached the top of its travel. The expansion of the air caused by the burning forces the piston downwards, turning the crankshaft. It is only during this stroke that the cylinder contributes towards the power generated by the engine.

Exhaust Stroke. During this stroke the intake valve remains closed but the exhaust valve opens. As the piston rises in the cylinder, pushed by the inertia of the crankshaft, the burned gas is forced out of the cylinder through the exhaust valve into the exhaust system. The exhaust valve then closes, the intake valve opens and the next induction stroke occurs.

The system of pipes that carries the fuel/air mixture to the cylinder is known as the *intake manifold* and the system of pipes carrying burned fuel to the exhaust is known as the *exhaust manifold*. The cylinder is fitted with two valves: one connecting it to the intake manifold, the other connecting it to the exhaust manifold system. These valves can be seen at the top of the cylinder in figure 12.8.

This description of the four stroke cycle is grossly simplified. In fact there is a great deal of sophistication in the shape of the cylinder, the shape of the piston crown, the positioning of the spark plugs, the positioning of the valves and the precise times at which they open and close. Section 12.4.14 on page 278 describes pre-ignition and detonation, two conditions that can occur if the burning of the fuel is not controlled precisely.

12.4.3 The Two Stroke Cycle

Generally, two-stroke engines are used on smaller aircraft, including many ultralights.

[11] The precise times at which the exhaust and intake valves open and close do not exactly align with the start of each stroke but, for simplicity, that detail is ignored here.

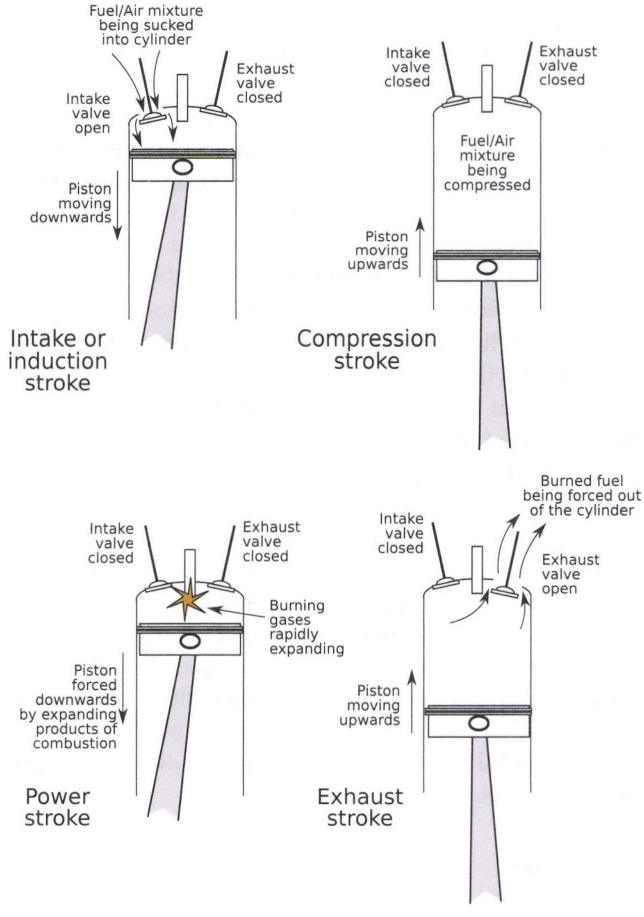

Figure 12.11: The Four Strokes of a Four-Stroke Engine

A two-stroke engine has to perform the same functions as a four-stroke engine: compress the fuel mixture, ignite the mixture to produce power, expel the exhaust gases and draw a fresh fuel mixture into the cylinder. The difference, as illustrated by figure 12.12, is that two of these functions occur on each stroke:

The Upstroke: Intake/Compression. During this stroke a mixture of fuel, air and lubricating oil in the cylinder is compressed as the piston moves upwards. This creates a vacuum in the crankcase,[12] sucking in more fuel, air and oil from the carburetor. Shortly before the piston reaches the top of its travel, the spark plug fires, igniting the mixture.

The Downstroke: Power/Exhaust. The ignited fuel/air/oil mixture forces the piston down in the cylinder. As the piston passes the exhaust port, most of the pressurised exhaust gases escape. As the piston continues down, it compresses the air/fuel/oil mixture in the crankcase. Once the top of the piston passes the transfer port, the compressed charge

[12] The section of the engine below the piston.

enters the cylinder from the crankcase and forces out any remaining exhaust. The cycle then repeats.

The two-stroke engine has one great power advantage over a four-stroke: it produces power every revolution of the crankshaft rather than on every second revolution. Together with its simplicity (effectively no valves with their associated timing), this means that a two-stroke engine produces more power for its weight.

Another advantage of two-stroke engines is that, because the lubricating oil is often mixed with the fuel, the engine will work in any orientation—four-stroke engines often have trouble with lubrication unless they are (almost) upright.

A two-stroke engine is, however, less efficient because the exhaust gases and intake mixture are in the cylinder at the same time and have to be kept separate by careful timing and shaping of the ports and cylinder. Even with this, there is some mixing and unburned fuel escapes through the exhaust port and already burned fuel remains for the next compression stroke. Other disadvantages of two-stroke engines include the expense of the oil that is burned with the fuel and the environmental pollution of the burning oil and escaping unburned fuel.

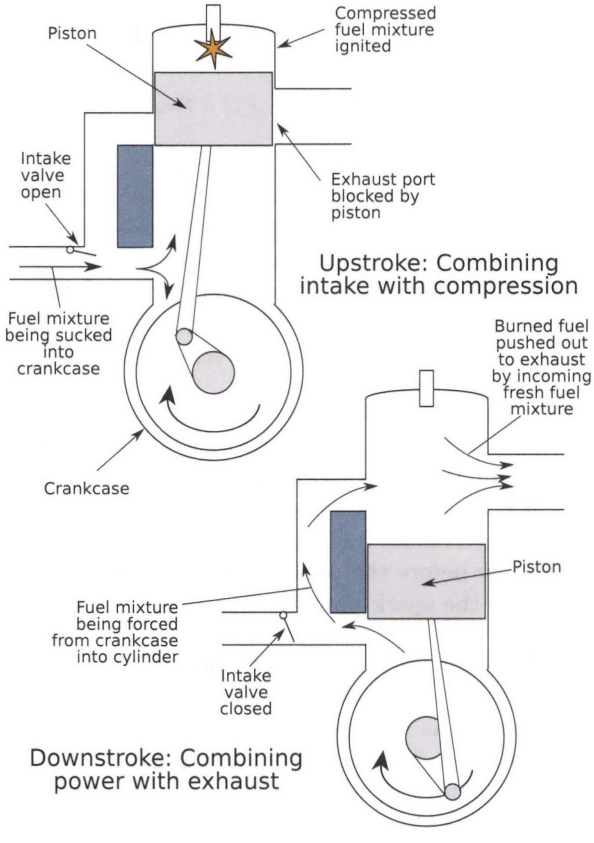

Figure 12.12: The Two Strokes of a Two-Stroke Engine

12.4.4 Diesel Engines

The principle of the diesel engine was patented in 1893 by Rudolf Diesel, and the first diesel engine developed specifically for aircraft was the Packard Radial Diesel of 1928.

A diesel engine is a very high pressure two- or four-stroke engine working effectively as described above except that the fuel/air mixture is ignited, not by a spark from a spark plug, but by injecting the fuel at high pressure into the cylinder as the compression completes; ignition occurring as a result of the high temperature of the compressed gas.

With cheap and plentiful avgas,[13] the fuel economy advantages of diesel engines have not, until recently, outweighed their disadvantages of extra weight. With avgas prices rising, and with the continued supply of 100LL avgas in doubt, manufacturers are again beginning to investigate the practicality of diesel engines for light aircraft—engines that would burn jet fuel.[14] As jet fuel is also widely available throughout the world, (and 100LL isn't), the development of diesel engines for light aircraft is making more practical sense to the general aviation industry.

12.4.5 Methods of Cooling

Most aircraft reciprocating engines are cooled by air, oil and fuel. The basic principle of air cooling, particularly on aircraft where the engine is mounted at the front, is to use air inlets on the engine cowling to direct the air flow from the aircraft's motion (the so-called "ram air") into the engine compartment.

There are two basic types of air cooling systems:

1. *Downdraft cooling* is designed to force air from the relatively high pressure area caused by the ram air down between the cylinders to a low pressure area below. The air inlets are typically behind and above the propeller and the outlets are located on the bottom of the engine cowling.

2. *Updraft cooling* is effectively the opposite—high pressure air below the engine is forced up between the cylinders to a low pressure area at the top. In these engines the air inlets are typically behind and below the propeller.

Each of these systems uses baffles to route the high pressure air. These are typically made of shaped aluminium with neoprene rubber or silicone rubber seals to prevent leakage.

[13] Aviation Gasoline: see page 278.

[14] Jet fuel is very similar to diesel and may be burned in most diesel engines.

To assist with the cooling, an engine normally has cooling fins on the cylinder heads and smaller fins on the cylinder barrels.

In addition to air, the oil and fuel also provide cooling for the engine. In most aircraft four-stroke engines, an oil cooler is mounted in the engine compartment and the oil flows through it as part of its normal cycle. To prevent the oil from getting too cold or too hot, a veratherm or thermostatic valve is incorporated into the oil cooler to direct the oil away from or through the oil cooler, depending on its temperature.

For engines of 200 horsepower (150 kW) and higher, the additional engine cooling needed for take off and climb can be created by supplying additional fuel to the engine. This excess fuel makes the fuel/air mixture very rich, lowering the exhaust gas temperature. The engine therefore produces less heat. Smaller engines typically do not need to use such fuel enrichment.

In most of Canada, additional baffles, known as winterisation kits, are used in cold weather (below $\approx -10°C$) to reduce the cooling airflow. It is important that these be removed in warmer weather to prevent over-heating.

Anecdote 43 *I was once acting as check-pilot for a Cessna 172 flight from Ottawa Rockcliffe to Kingston, Ontario, when, a few miles after departing, I noticed that the oil temperature had gone off the scale. We quickly checked the oil pressure which was normal. We accepted ATC vectors to the nearest airport, Ottawa Carp, and, after landing, found that the winterisation kit had not been removed, even though the outside air temperature was above the recommended limit.*

12.4.6 Exhaust Systems

Diagrams such as figures 12.11 and 12.12 give the impression that the exhaust system is just a simple tube leading burned gases from the engine to the outside air. This is far from the full story: a well-designed exhaust system can generate substantial extra power from a reciprocating engine.

The document *Aircraft Exhaust Systems IV*, sponsored by the Experimental Aircraft Association (EAA) and available from that group's website, contains the results of a study performed on the exhaust system of a Lycoming IO-360 A1B6, a 4-stroke aircraft engine. The conclusions from this study include the following:

- Immediately before the exhaust valve opens (just before the end of the power stroke) the pressure in a cylinder's exhaust system is lower than the ambient atmospheric pressure. As the exhaust valve opens, the pressure rises very quickly (this is called the "P"-wave). This rise in pressure is not smooth because of imperfections in the exhaust system, turbulence of the gases themselves and, in systems where the exhausts from each cylinder are combined in a collector, because of conflicting pressures from other cylinders.

  In a perfect engine, the pressure in the cylinder would drop below the ambient atmospheric pressure before the piston starts on its upward exhaust stroke. This would provide suction to help lift the piston. In practice, the rising piston initially pushes against higher than ambient pressure in the cylinder, causing a loss of power.

  By careful design of the exhaust system, the period of positive pressure after the exhaust valve opening can be reduced, thus inducing the engine to produce more power.

- It would be possible to use a computer to calculate a Fourier Transform and so determine the frequencies present in the changing pressures at the exhaust port to build an excellent noise-cancelling muffler. These would be particularly suitable for aircraft engines because of their limited range of rotation speeds, but there is no record of this having been done.

- The thrust from a well-designed exhaust system, particularly at high altitudes and high power settings, can be about 17 to 21 pounds-force (76 to 93 newtons). Properly directed, this could provide additional thrust for the aircraft.

Another use of the pressure created in the exhaust system is to turn a turbine to compress the intake air—see *Turbocharging* on page 272.

12.4.7 Ancillary Controls

The term *Ancillary Controls* is given to a collection of effectively unrelated controls in the aircraft:

1. Carburetor heat control: see *Carburetor Icing* on page 274.

2. Mixture control: see *Mixture Controls* on page 273.

3. Environmental controls: these are used to regulate cabin heat, cabin air, windscreen defrosting, etc. in much the same way as they are deployed in a car (except that in many aircraft they are much less efficient than those in a car. In many Cessna 172s, for example, cabin heat stops when the carburetor heat is turned on).

12.4.8 Density Altitude/Humidity

The concepts of pressure altitude and density altitude are described in section 11.4.2 on page 241, particularly in regard to the effect of high density altitudes on takeoff and climb performance. However, a high density altitude affects not only the takeoff performance, but also the power generated by a normally aspirated (i.e., not turbocharged) engine.

The density altitude of an airport (or cruising level) A is the altitude of an airport B which is at standard temperature, pressure and humidity and has the same air density as A.

Thus, if an airport is at 500 ft ASL and its atmospheric conditions are standard (the sea-level temperature is 15°, the sea-level atmospheric pressure is 29.9213″ Hg and its dew point is 0°C), then its density altitude will also be 500 ft ASL. If its temperature is higher than standard, or its pressure is lower or its relative humidity is higher, then the air will be less dense and, to the aircraft, the airport will appear to be higher than 500 ft ASL.

The only practical way to calculate density altitude is to use an aviation calculator. However, these calculators are, in general, inaccurate because they do not take humidity into account. Higher than standard humidity does not significantly affect takeoff and landing distances, but it can reduce engine power considerably.

Exercise 99 *Lakeville airport is at 1,066 ft above sea level. The temperature is 25° C, the atmospheric pressure is 29.36″ Hg and the dew point is 10° C. What is the density altitude of Lakeville and what does this concept mean?*

Possible answers to the exercises in this chapter are given at the end of the chapter, starting on page 281.

As a first approximation, the effect of reduced air density on a normally-aspirated engine is proportional to the density:

$$\text{Output power} = \text{Rated power} \times \frac{d_1}{d_s} \qquad (12.1)$$

where d_1 is the air density at the engine intake and d_s is the standard density of 1.226 kg per cubic metre at sea level.

Exercise 100 *At sea level on a standard day the normally-aspirated engine in your aircraft is rated to produce 116 Horsepower (86.5 kW). You are taking off from an airport with a density altitude of 6,000 ft ASL.*

Altitude (Feet ASL)	Air Density (kg/cubic metre)	(lbs/cubic ft)
Sea Level	1.226	0.0765
1000	1.190	0.0743
2000	1.155	0.0721
3000	1.121	0.0700
4000	1.088	0.0679
5000	1.056	0.0659
6000	1.024	0.0639
7000	0.993	0.0620
8000	0.963	0.0601
9000	0.934	0.0583
10000	0.905	0.0565

Figure 12.13: Air Densities

Using the values for atmospheric density given in figure 12.13, estimate the power output of the engine.

12.4.9 Super- & Turbocharging

The terminology of *supercharging* and *turbocharging* is confusing, but the basic idea is simple: to compensate for the reduction in external air pressure at higher altitudes (see *Mixture Controls* on page 273) by pressurising the intake air used in the combustion process. In a non-super/turbocharged engine it is only the external air pressure that forces air into the cylinder during the induction stroke of the piston. As an aircraft climbs, this external pressure drops and so does the engine power.

The first patent for a supercharger was submitted in 1905 by a Swiss engineer called Alfred Büchi. It describes an external compressor used to pressurise the intake air to produce more power from a reciprocating engine.

This basic concept was later extended to use the engine's own exhaust gases to turn the turbine that compressed the intake air: known as turbosupercharging. Teledyne Continental still uses the term *turbosupercharging* for this, but most people abbreviate it to *turbocharging*.

A turbocharger consists of a turbine and a compressor sharing an axle: see figure 12.14. The turbine is rotated by exhaust gases from the engine and drives the compressor, compressing ambient air and delivering it to the air intake manifold of the engine at higher pressure. This causes a greater mass of air to enter the cylinder, which increases engine power, particularly at high altitudes where the external air is less dense.

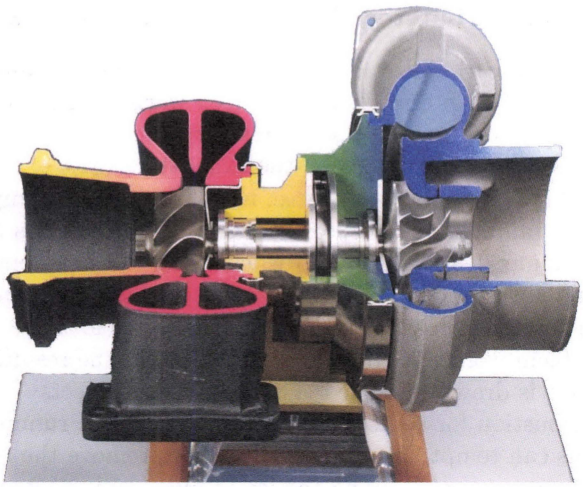

Figure 12.14: A Turbocharger

The pressure created by the turbocharger is controlled by means of a *wastegate*: a valve that diverts the exhaust gases away from the turbine when the pressure becomes too great, thus protecting the engine and the turbocharger.

12.4.10 Carburation

A carburetor produces a suitable mixture of air and fuel to be passed to the cylinder. The correct mixture is defined by weight (so many grammes of fuel to so many grammes of air) rather than by volume (so many cubic centimetres of fuel to so many cubic centimetres of air).

Carburetors are not needed on fuel-injected engines (including diesel engines)—see section 12.4.11.

Theory of Operation

The purpose of the carburetor is:

1. to measure an appropriate amount of incoming air
2. to mix that air with fuel to ensure that a proper charge enters the cylinders under all operating conditions.

Figure 12.15 illustrates the concept of the carburetor:

- Fuel is held in a reservoir where its level is kept constant by a float valve which opens when the level falls (similar to the one seen in a normal domestic toilet tank, but a lot smaller).
- The fuel in the reservoir, regulated by the mixture control in the cockpit (see below), flows to the tip of a nozzle within the carburetor.

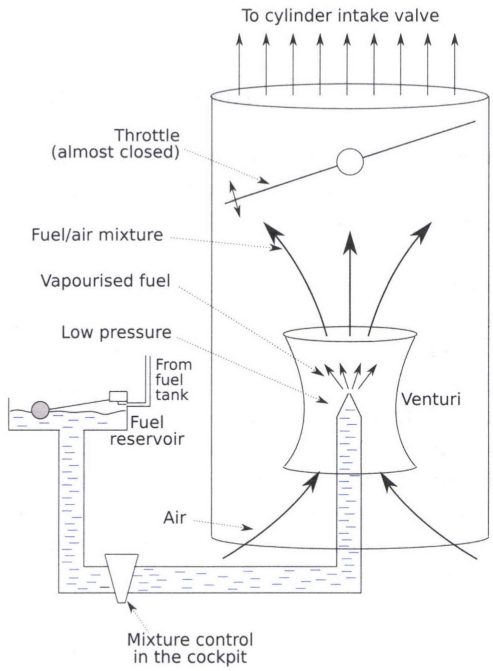

Figure 12.15: Principle of Operation of a Carburetor

- Incoming air, sucked by the piston descending on its intake stroke, passes through the carburetor. In particular, it passes through a venturi—a constriction in the tube.
- As described in section 9.2.5 on page 167, when fluid flows through a constriction, three things happen to it: it speeds up, its temperature drops and its pressure drops.
- The low pressure at the nozzle causes fuel to be sucked out and vapourised in the air stream, creating a mixture of fuel and air to be fed to the cylinders.
- The amount of the fuel/air mixture drawn by the suction of the intake stroke allowed to reach the cylinders is controlled by the throttle.

Fuel-Air Mixture/Mixture Controls

For maximum engine performance, there is an optimal ratio of fuel and air in the mixture. If there is too much fuel in the mixture, the mixture is said to be *rich*; if there is too little fuel, it is said to be *lean*.

As an aircraft climbs, the surrounding air becomes less dense. Unless steps are taken, an air/fuel mixture that is correct before takeoff will become too rich at altitude as the same amount of fuel is being mixed with less air. Under these conditions, the engine will not produce maximum power, the spark plugs will have a tendency to foul, the engine will run cooler than is

optimal, and unburned fuel will be ejected in the exhaust.

There are two ways to handle this situation:

1. **Increase the amount of air** artificially. This is known as supercharging or turbocharging and is described in section 12.4.9.

2. **Reduce the amount of fuel.** This is the technique employed on aircraft without super- or turbochargers and is achieved by means of the mixture control in the cockpit—see figure 12.15. This controls the amount of fuel reaching the carburetor. A pilot or computer adjusts the mixture control to give maximum engine power as indicated by the tachometer (see page 277), manifold pressure gauge (see page 277) or exhaust gas temperature gauge (see page 275).

   The exhaust gas temperature gauge tends to be more reactive than the tachometer. When flying with a fixed pitch propeller, a pilot can generally use it to find the optimal position of the mixture control and then check with the tachometer.

   Of course, it is important to enrich the mixture during a descent or it may become so lean that the engine stops.

Carburetor Icing

As the incoming air flows through the venturi in the carburetor, both its temperature and pressure drop. The drop in pressure is effective in sucking the fuel out of the nozzle, but the drop in temperature can be dangerous. If it causes moisture in the air to freeze, then ice can form around the throttle and restrict the flow of mixture to the engine. A pilot normally detects this by a drop in engine power, indicated by a drop of revolutions per minute (fixed-pitch propeller) or manifold pressure (constant speed propeller), but it should be anticipated in moist air (relative humidity greater than 50%) at any temperature between about 15°C and −5°C. Below −5°C the incoming air is unlikely to contain enough moisture to cause icing.

If the aircraft is equipped with a carburetor mixture temperature gauge then this provides a direct reading to the pilot of the temperature of the mixture. In this case the temperature of the mixture should be held above 4°C by use of the carburetor heat control.

One of the clearest summaries of carburetor and induction icing (see section 12.4.11) is SafetySense Leaflet number 14 issued by the UK Civil Aviation Authority and available on the Internet at `https://publicapps.caa.co.uk/docs/33/20130121SSL14.pdf`.

Use of Carburetor Heat & its Effects on Mixture

To avoid carburetor icing, many general aviation aircraft are fitted with a mechanism to feed warmer, drier air into the carburetor—the carburetor heat control. This air is normally warmed by the exhaust.

The best policy, of course, is to avoid any buildup of ice by applying carburetor heat at regular intervals (as recommended in the POH) when flying in conditions conducive to icing. If icing does occur, then applying carburetor heat may initially appear to make the problem worse. As the ice begins to melt, the resulting water is drawn into the cylinders where it affects combustion for a short time, producing rough running. This can tempt an unprepared pilot to remove the carburetor heat, leaving the ice in place and eventually causing fuel starvation and engine failure.

Note that, if the outside air temperature is below that where carburetor icing can form, applying carburetor heat can actually invoke icing by raising the temperature to one where icing occurs.

For some aircraft, it is recommended that the throttle be put to full power when carburetor heat is applied, thus opening the throttle valve and increasing the amount of heated air passing through the carburetor. This speeds up the melting of the ice. The aircraft's POH will give details of whether full throttle is recommended.

One unwanted effect of applying carburetor heat is that, because the warmer air has a lower density than the cold air, the balance of the mixture changes, becoming rich. This is reflected in a reduction in both power and exhaust gas temperature. Generally, however, carburetor heat is not applied for a time long enough to make leaning with the mixture control worthwhile.

12.4.11 Fuel Injection

Principle & Operation

Fuel injection provides an alternative to the use of a carburetor: instead of mixing the fuel and the air in the carburetor at low pressure and then introducing this into the cylinder, the fuel is injected under high pressure (which causes vapourisation through a process known as *pressure blast atomisation*) through a nozzle directly into the airflow at the port to the intake valve (gasoline engines) or directly into the cylinder (diesel engines).

Injection may be timed to occur just before the piston reaches the top of the compression stroke or may be continuous. Continuous flow systems are particularly used in aircraft engines because of their basic simplicity: the only "moving part" is the fuel pump providing the pressure for the fuel injection. Fuel injection is used in all diesel and many gasoline engines.

The first fuel injected engine was created by Rudolf Diesel and used powdered coal for the fuel. Diesel found that coal caused the engine to clog and, in many cases, to explode and so he experimented with gasoline. The problem with this was that the expansion of the gasoline and the compressed air that propelled it caused the mixture to cool, reducing the efficiency of the engine. The first practical fuel-injected engine was a diesel engine designed by Robert Bosch in 1912. Bosch used a pump to feed the fuel under high pressure into the cylinder as the piston completed the compression stroke. The heat of the compressed air caused the fuel to burn, providing the power stroke. Bosch's basic principle of diesel engines remains effectively unchanged.

Induction Icing & Alternate Air

Fuel-injected engines do not suffer from carburetor icing—they don't have carburetors! They can, however, suffer from *induction ice*: snow or ice forming against the induction air filter and blocking it. This type of induction ice can form whenever the airframe is below 0°C and is flying in snow, sleet or clouds. It also occurs when an aircraft flies in super-cooled water droplets: freezing rain. Note that induction ice can form on carbureted as well as fuel-injected engines.

Alternate Air (sometimes called *Induction Heat*) is installed on fuel-injected engines to guard against induction ice. The alternate air intake is normally fitted inside the engine cowling downstream of the normal air intake. This alternate air is warmed by engine heat, even though it does not normally pass through a heat exchanger.

12.4.12 Reciprocating Engine Instruments

Exhaust Gas Temperature

The temperature of the exhaust gas is measured just after it leaves the cylinder. On some aircraft only one exhaust gas temperature probe is fitted, on others one is fitted into each exhaust manifold.

On a reciprocating engine without FADEC (see section 12.3.6), the exhaust gas temperature can be used, together with the tachometer, to determine when leaning has resulted in a correct fuel/air mixture. As the mixture is leaned towards the optimal value, the exhaust gas temperature rises. Once the optimal value is passed, its temperature starts to fall again.

Oil Pressure

Section 605.14 of the CARs states that

> No person shall conduct a take-off in a power-driven aircraft for the purpose of day VFR flight unless it is equipped with ... an oil pressure indicator for each engine employing an oil pressure system.

The oil pressure gauge indicates the state of the oil system by measuring the pressure of oil supplied to the engine. The actual location of the pressure transducer varies from engine to engine: Lycoming engines often have it directly at the oil pump whereas Teledyne Continental engines have it much further downstream. This can be seen during engine starting: the Lycoming engines will typically register oil pressure within a few seconds whereas Continental engines can take up to half a minute.

Oil pressure systems operate either by having a pressure transducer on the engine with electrical connection to a gauge in the cockpit or by bringing the pressurised oil through a narrow tube to the back of the gauge where the pressure is displayed directly. A drawback of this latter method is that the gauge will read incorrectly if air gets into the tube.

For more details about the lubrication system of an aircraft, see section 13.3 on page 292.

Oil Temperature

Section 605.14 of the CARs states that

> No person shall conduct a take-off in a power-driven aircraft for the purpose of day VFR flight unless it is equipped with ... an oil temperature indicator for each air-cooled engine having a separate oil system.

The oil temperature gauge measures the temperature of the engine oil. The precise point at which the temperature is measured varies from engine to engine but on many light aircraft engines (e.g., the Teledyne Continental O-200A used in Cessna 172s) it is mounted at the oil screen.

On the cockpit display, a green area shows the normal operating range and the red line indicates the maximum allowable temperature. Changes in oil temperature occur more slowly than changes in oil pressure and this is particularly noticeable after starting a cold engine, when it may take several minutes for the gauge to show any increase in oil temperature.

A pilot should check oil temperature and pressure periodically during flight and be familiar with the normal position of both gauges—many have not been re-calibrated since the aircraft was built and changes in readings are more important than actual values. High temperature readings may indicate a plugged oil line, too little oil, a blocked oil cooler or a defective

temperature gauge. See also anecdote 43 on page 271. Low temperature indications may indicate improper oil viscosity during cold weather operations.

For more details about the lubrication system of an aircraft, see section 13.3 on page 292.

Fuel Flow

Three main techniques are used to measure the rate of fuel flow to the engine:

1. **Differential pressure.** Devices measure the difference in pressure at each end of the fuel feed tube and, given the tube's diameter, carry out the necessary arithmetic to calculate the flow rate.

2. **Velocity.** Devices measure the fuel flow directly, by placing an impeller (a small turbine) in the fuel line where it is turned by the fuel as it flows past. A transducer picks up pulses from the impeller as it rotates (often by detecting the magnetic field changes caused by the rotating metal) and times these to deduce the fuel flow. These devices are sensitive to changes in the density of the fuel and for this reason, in large aircraft, the temperature of the fuel is also measured and the necessary adjustment made.

3. **True Mass.** For turbine aircraft it is important to be able to measure the mass (rather than the volume) of fuel that is flowing, as the energy from the engine is proportional to the mass, irrespective of the density.

   A true mass fuel flow transducer consists of an impeller (turbine) as in velocity measurement, the impeller turning a drum that contains a second turbine, mounted with its vanes parallel to the fuel flow. As the fuel passes through the rotating drum, its momentum (the product of its mass and speed) causes the second turbine to lag behind the drum, acting against a spring. The difference in phase between the rotation of the drum and of the turbine within it is measured magnetically and is used to deduce the mass flow of the fuel.

   In comparison with velocity (impeller) mechanisms, true mass transducers are far more complex and normally slower to respond to changes in the flow, their response time being measured in seconds rather than milli-seconds.

Whatever the technology used to measure the flow, the indicator available to the pilot will at least display the fuel flow rate to each engine and, with more modern instruments, keep track of the amount of fuel consumed and alert the pilot when the remaining fuel drops below a pre-set minimum.

When installing a fuel flow measurement system in a general aviation aircraft there are several points to be noted: some fuel flow transducers cannot handle fuel being returned from the carburetor to the fuel tank and some can only operate on pumped (rather than gravity-fed) fuel systems.

Anecdote 44 *I remember my surprise when I first flew an aircraft with a fuel flow meter. I had reached cruise altitude, levelled out and settled back to enjoy the view when I glanced at the fuel flow gauge. It was showing a fuel flow of over 13 gallons per hour when I expected 9! It took me a moment to realise that I had forgotten to lean the mixture, and doing so reduced the flow to the value I expected. I had learned during my training that, unless the mixture was leaned, fuel flow would be much greater than defined in the POH. This incident made me realise that the difference is not trivial—it could make the difference between arriving at a destination or running out of fuel miles short.*

Cylinder Head Temperature

Most reciprocating engines have a means of measuring the temperature of at least one of the cylinders and often of each cylinder: the probe is typically a thermocouple inserted either into a receptacle on the cylinder designed for the purpose or, in some simple engines, under the spark plug, replacing the spark plug washer.

Monitoring the cylinder head temperatures allows the pilot to tell whether overheating is occurring and whether one cylinder is running cooler than the others. A cold cylinder, particularly if the exhaust gas temperature is normal, may indicate a broken exhaust valve or detonation (see section 12.4.14). The early detection of these conditions could possibly save the engine from serious damage.

Fuel Pressure

In many small, high-wing aircraft no pump is needed to move the fuel to the engine—gravity feeds the fuel from the tanks to the engine. In aircraft where the fuel is pumped to the engine, a fuel pressure gauge is fitted to allow the pilot to check the operation of the pump. The value displayed normally indicates the pressure at the carburetor or, for fuel-injected engines, at the fuel controller.

Fuel Quantity

Section 605.14 of the CARs states that

> No person shall conduct a take-off in a power-driven aircraft for the purpose of day VFR flight unless it is equipped with ... a means for the flight crew, when seated at the flight controls, to determine the fuel quantity in each main fuel tank.

but there is no regulation that defines the required accuracy of a general aviation fuel gauge. Inaccuracy in the fuel gauges has led to an unfortunate habit of general aviation pilots ignoring them and relying solely on flight time and a knowledge of the state of the fuel tanks at takeoff.

Anecdote 45 *I witnessed a near accident when one of my solo students took off to practise circuits in a Cessna 172 with full fuel tanks. After about 45 minutes of circuits she radioed to say that she would make her next landing a full stop. I encouraged her to fly a couple more circuits, but she said she was too tired and intended to stop (good pilot decision-making). As she taxied to the pumps, fuel was seen to be pouring from the bottom of the engine—the fuel drain had worked its way open. The aircraft was refuelled with over 35 gallons of fuel into a 38 gallon tank. It is likely that another circuit would not have been completed because of fuel exhaustion. I asked the student why she had not noticed the problem when inspecting the fuel gauges during her downwind checks. She said she had noticed them reading low, but was sure that the tanks had been full at takeoff and had only flown for 45 minutes, and so was disregarding the readings.*

The actual mechanism used to measure the fuel level in a tank varies between aircraft types. In large aircraft where there are many distributed fuel tanks[15] a capacitive system is used. An electrical capacitor consists of two conductive plates with an insulating material between. The characteristics of the insulation can be measured electronically. In an aircraft, the fuel is used as the insulating material and two metal plates in the fuel tanks are the conductive plates. As the amount of fuel changes, so does the capacitance of the system and this can be measured electronically. The capacitance measurements are fed to a computer that compensates for the aircraft's angle of bank.

In contrast, many light aircraft have some form of float (often containing a magnet) in the fuel tank whose position can be read and displayed on an electric gauge. This gauge is normally inaccurate when the aircraft is banking in an unco-ordinated turn.

Some vintage aircraft have a simple tube, visible to the pilot, indicating the fuel level in the tanks.

[15]The Airbus A320, for example, has 5 to 7 tanks, the precise number depending on model number.

Tachometer

Section 605.14 of the CARs states that

> No person shall conduct a take-off in a power-driven aircraft for the purpose of day VFR flight unless it is equipped with ... a tachometer for each engine and for each propeller or rotor that has limiting speeds established by the manufacturer.

A tachometer on a rotating engine displays the speed of rotation, typically as hundreds of revolutions per minute.

Tachometers built into aircraft are typically electrical generators being driven from the propeller shaft. The faster the generator is turned, the higher the voltage generated. This voltage is then displayed to the pilot.

Portable tachometers, often used to calibrate in-built tachometers, normally work optically: photo-cells sense the propeller blades passing and measure the time between them. A simple calculation (based on the number of blades) gives the rotational speed.

Manifold Pressure

Section 605.14 of the CARs states that

> No person shall conduct a take-off in a power-driven aircraft for the purpose of day VFR flight unless it is equipped with ... a manifold pressure gauge for each reciprocating engine equipped with a variable-pitch propeller, reciprocating engine used to power a helicopter, supercharged engine and turbocharged engine.

This instrument measures the pressure in the intake manifold of a reciprocating engine, particularly one with a constant speed propeller. The manifold pressure is measured between the throttle (see figure 12.15) and the cylinder. If the throttle is closed (i.e., the path to the cylinder is blocked), then the pressure at the intake to the cylinder will be low as the piston moves downwards on its intake (induction) stroke. If the throttle is wide open, then the pressure at the intake to the cylinder will effectively be the external atmospheric pressure (if the engine is normally aspirated, i.e., not supercharged).

The manifold pressure is therefore a reasonable measure of the power being produced by the engine—higher manifold pressure being associated with higher power. Of course, even at a constant throttle setting, the manifold pressure will drop as the aircraft climbs: at approximately 1″ Hg per thousand feet.

For any given propeller speed (in revolutions per minute) there is a manifold pressure that should not be exceeded. If the throttle is set to give a manifold pressure greater than this, the pressure could place stress on the cylinders and eventually cause engine failure.

Anecdote 46 *The first time I flew an aircraft with a constant speed propeller (a Katana DA20) I read about the acceptable manifold pressures in the handbook but didn't really understand the concept. During the flight I found that the manifold pressure was dropping (I was climbing but the connection didn't hit me) and I returned to the airport to report the problem. I found that, as I approached the airport (and descended for landing), the problem seemed to clear up. I suspect the instructors to whom I reported the "problem" are still talking about the pilot who, flying a normally aspirated engine, didn't expect the manifold pressure to drop with altitude.*

In flight, ice buildup on the induction air filter or carburetor icing (see *Carburetor Icing* on page 274 and *Induction Icing* on page 275) is often first detected through a reduction in the manifold pressure.

12.4.13 Fuels

There are two types of fuel used in aircraft reciprocating engines: MOGAS and AVGAS. For more details about the fuel system itself, see section 13.4 on page 294.

Mogas

The term *mogas* is used in the aviation community to refer to automobile fuel. The main disadvantages of mogas when used in aircraft are that:

- as bought from a service station, its composition changes throughout the year: there are four *seasonal grades* in Canada, each with a different vapourisation characteristic. This can be particularly dangerous for an aircraft making a flight from one climatic region to another: e.g., flying south from Canada in the winter with Canadian winter-grade mogas in the tanks.
- it vapourises very easily. This can cause vapour locks in the fuel feed, particularly when starting a hot engine, and aggravates carburetor icing—such icing occurs at higher ambient temperatures and lower humidity with mogas than with avgas.
- it can have deleterious effects on the plastics used within aircraft fuel tanks and systems.
- its use is normally not underwritten by engine manufacturers—using mogas may invalidate any warranty on the engine.

To avoid some of these problems, particularly the issue of vapourisation, Transport Canada used to restrict the use of mogas to flights lower than 6,000 ft ASL and temperatures lower than 24°C. In its bulletin number TP 10737E, entitled *"The Use of Automobile Gasoline (MOGAS) in Aviation"* issued in 1993, Transport Canada removed this restriction, based on research which showed that there was no significant difference between mogas in Canada and in the USA, and the restriction had never existed in the USA.

One significant advantage that mogas has over avgas for aviation use is its lower concentration of lead: 5 mg/litre rather than 560 mg/litre. Lead in fuel has environmental impacts and can cause sticking valves, pre-ignition, detonation (see section 12.4.14), plug fouling and other negative effects.

Mogas is coloured red, orange, yellow or is left colourless. It should never be mixed with avgas.

Avgas

Avgas grades are described by their octane rating (see page 295). Typically two ratings are given: one for the lean mixture and one for the rich mixture. For example, avgas 100/130 has a lean mixture rating of 100 and a rich mixture rating of 130.

In the past, there were many different grades of avgas in general use including 80/87, 91/96, 100/130, 108/135 and 115/145. However, with decreasing demand these have reduced to one grade: avgas 100/130. This fuel is commonly termed avgas 100 and, in a lower-lead form, it is known as avgas 100LL (low lead).

Avgas 100LL is coloured blue and avgas 100 is coloured green.

In February 2008, Teledyne Continental's president, announced that the company was very concerned about future availability of 100LL avgas and would therefore develop a diesel engine in the 300 horsepower (220 kW) range for certification in 2009 or 2010. This did not occur.

12.4.14 Detonation & Pre-ignition

Detonation and pre-ignition are different phenomena but are linked because each can cause the other.

Both pre-ignition and detonation interrupt the way the fuel and air mixture burns in the cylinder. The burning should start with the spark plug firing, should originate at the spark plug and spread in a steady, even fashion across the cylinder. The burn should move across the cylinder and be quenched against the (cooler) walls and the piston crown. At the end of the burn, there should be no remaining fuel-air mixture.

Pre-ignition interrupts this normal operation by causing the fuel and air mixture to ignite before the spark plug fires. The reason for pre-ignition is typically some hot spot in the cylinder acting as a glow-plug: an

overheated spark plug tip, carbon deposits or a burned exhaust valve. Clearly, the fuel and air mixture igniting too early upsets the timing of the engine and subjects the cylinder to intense pressures and temperatures as the engine works to compress a rapidly-expanding, burning mixture. The damage that can occur from pre-ignition includes cracked ceramic on the spark plug and erosion (including in extreme cases a melted hole) at the crown of the affected piston.

Detonation occurs after the spark plug has fired. As the burn moves across the cylinder its progress is interrupted when the unburned mixture, under increasing pressure and heat from the normal burning process, spontaneously combusts, ignited by the intense heat and pressure. In effect, the fuel in the mixture remaining in the cylinder lacks sufficient octane rating to withstand the combination of heat and pressure. The use of fuel with too low an octane rating for the engine is a common cause of detonation. Detonation causes a very high, very sharp pressure spike of short duration in the combustion chamber. Thus, in contrast with normal combustion, detonation is not a controlled burning; rather it is an explosion. Detonation can cause mechanical damage (e.g., broken ring lands), abrasion (e.g., pitting of the piston crown) and overheating (causing scuffed piston skirts due to excess heat input or high coolant temperatures).

Generally, turbocharged engines are more susceptible to detonation than equivalent non-turbocharged models, and engines with higher compression ratios are more likely to exhibit detonation than engines with lower compression ratios.

The normal pilot-induced causes of detonation are:

1. running the engine with a manifold pressure that is too high for the engine speed and mixture setting: always refer to the Pilot's Operating Handbook for manifold pressure settings. This was a particular problem in supercharged and turbocharged engines before pressure relief valves and automatic wastegates were introduced. If the wastegate[16] is inadvertently left in the closed position when the pilot applies full throttle for takeoff or a go-round, it can produce a manifold pressure of 60″ Hg or more and a failure of the engine.

2. running at high power settings with the mixture too lean. For example, it is recommended that Lycoming engines not be leaned at power settings which produce more than 75% of rated engine power unless this operation is approved in the Pilot's Operating Handbook.

Figure 12.16 illustrates some of the typical damage caused by pre-ignition and detonation on a piston.

[16] See page 272 for a description of the wastegate.

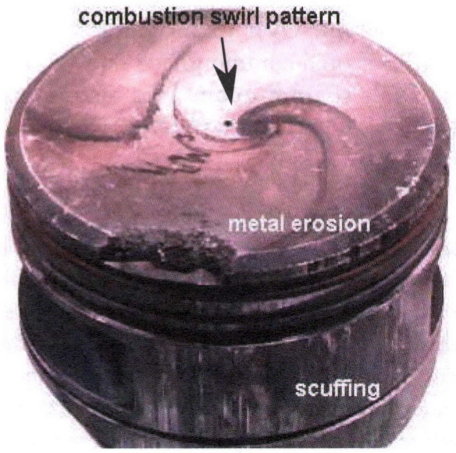

Figure 12.16: A Piston after Pre-ignition and Detonation (Sacramento Sky Ranch)

12.4.15 Vapour Lock

Vapour lock affects gasoline-fuelled aircraft engines when the liquid fuel changes from liquid to gas before it reaches the cylinder. This disrupts the operation of the fuel pump, causing loss of feed pressure to the carburetor or fuel injection system, resulting in a partial or complete loss of power.

Vapour locks can be caused by using a fuel that is too volatile (e.g., MOGAS) or by trying to start a hot engine.

The issue of vapour lock has led to a number of airworthiness directives being issued. AD 72-07-02, for example, requires that on Cessna 172 models up to and including the 172K, *"To reduce the possibility of engine power interruption at altitudes above 5,000 ft caused by vapour formation in the fuel lines, ... the airplane must be operated on a single fuel tank immediately upon reaching cruise altitudes above 5,000 ft."*

12.4.16 Primers

With reciprocating engines, it is sometimes necessary to inject fuel directly into the cylinder intake manifolds to help with starting. For non-fuel injected engines, a pump, often manually operated, is provided for this; in a fuel injected engine the fuel boost pump provides this priming.

In the case of a manual pump, it is important to lock it when not in use. If the pump could operate in cruise then the result would be an excessively rich mixture.

12.5 Electric Motors

By the time you read it, the information in this section will have evolved. At the time of writing,

electrically-driven aircraft lie between advanced research and science-fiction. Over the next few years, either such aircraft will become commonplace and the earlier sections of this chapter quaint and historic, or such aircraft will be found to be impractical, making this section irrelevant.

Mark Moore of NASA has said:

> *I believe that distributed electric propulsion is one of the biggest technology changes in aerospace since the invention of the turbine engine. Turbines, when they were introduced, were essentially laughed at by many because they thought it couldn't replace the wonderful internal combustion engines that existed. [But] within 10 to 20 years they completely replaced that technology. I think we're at that same kind of replacement of technology—that within 10 to 20 years, distributed electric propulsion will replace turbine engines on a small scale, then we'll see it on a larger scale.*

Electric motors certainly have significant advantages over either reciprocating engines or turbines: they are quieter, they vibrate less, they do not consume limited fossil fuels and they are much simpler, having fewer moving parts.

Research, design and development of electrically-powered aircraft has become a set pathway for the future of aviation, not least for the decarbonizing benefits such options present for the environment. One subset of this pathway lies with research into distributed electric propulsion (DEP), a means by which electrification is tying together aerodynamics, propulsion and flight control in unorthodox ways. Battery-electric, hybrid-electric, and hydrogen–electric solutions are reshaping the ways aircraft look and operate, typically employing arrays of electric-powered propellers providing lift, thrust and control in new and innovative designs. Though discontinued in 2023, NASA's X-57 concept was configured with a large number of small electric motors distributed along the leading-edge of its wings. This layout, as shown in figure 12.17, was studied to evaluate the effects of air being forced over the wings directly by the propellers, thereby increasing their lift-coefficient at low airspeeds while concurrently decreasing their induced drag. NASA's expectation for the X-57 was a lift-to-drag ratio of 22 compared to approximately 16 for an Airbus or 7 for a Cessna 152. Experimental designs of similar configuration to the X-57 continue to be tested, not least by such as Daher, Safran and Airbus.

However, the idea of an electrically-powered, heavier-than-air aircraft is not new. The first was a tethered helicopter flown in 1917. The electrical power source remained on the ground and power was fed to the helicopter through the tethering wires. This illustrates

Figure 12.17: NASA's X-57 Concept (NASA)

the primary problem with electrically-powered flights: the weight of the batteries or fuel cells that need to be carried.

More recently, Solar Impulse 2 was built in 2014 with four electrically-driven propellers. Using solar cells on its abnormally large wings to recharge its batteries, it completed a round-the-world trip in 2016.

Since 2010, a significant amount of research has been aimed at exploring the feasibility of electric motors for both light aircraft and airliners. Manufacturers and airline carriers have been working together to test hybrid regional aircraft. It is estimated that such an aircraft could be up to 80% cheaper to operate per passenger-kilometre than a Dash-8.

In 2017, Airbus partnered with Rolls-Royce and Siemens to develop a hybrid aircraft with two of the four engines being electrically-driven.

Other companies have targeted specific markets such as pilot training. Training aircraft typically fly for less than ninety minutes in close proximity to the departure airport, and often in noise-sensitive areas. An aircraft that is cheaper to operate and quieter in flight would be welcomed by most flight schools. The Bye Aerospace Sun Flyer 2 was introduced in 2016 for precisely that market. It is a two-seater with over three hours flight duration and batteries that can be exchanged very quickly.

The Bye Aerospace Sun Flyer 4 was announced as a four-seater, full IFR aircraft in 2017.

12.6 Reverse Thrust

The primary purpose of an engine, whether piston, turbine or electrical, is to provide thrust. After landing, or during an aborted takeoff, it is useful also to be able to provide reverse thrust to slow the aircraft down.

The mechanisms for producing reverse thrust differ between a propeller-driven aircraft and a turbine.

For propeller-driven aircraft, the technique is to change the pitch of the propeller through its zero-thrust position to a point where it is thrusting the air forwards.

For turbine engines, it is impossible to stop and restart the turbine in the opposite direction; rather the flow of air from the rear of the turbine has to be reversed. There are three mechanisms for achieving this:

1. Target or Bucket types. These are illustrated in figure 12.18. In operation, the nozzle at the rear of the turbine opens, under hydraulic power, to redirect some of the air forwards.

2. Cascade or Clam-Shell types. These are similar to target types in that they redirect the exhaust forwards, but the air that is redirected is the bypass-air (see section 12.3.3). This means that they are normally used only on turbofan (rather than turbojet) engines.

3. Cold-Stream type. These open the engine cowling that normally contains the bypass air that has passed through compression, but not combustion (hence the term "cold-stream"). This bypass air is then directed outwards and partially forward, creating reverse thrust and drag.

Figure 12.18: Reverse Thrust Buckets (Adrian Pingstone)

Generally, it is extremely undesirable for reverse thrust to be selected when the aircraft is not on the ground, and many accidents have happened when this has accidently (Lauda Air Flight 004 in May 1991) or deliberately (Japan Airlines Flight 350 in February 1982) occurred. However, for some aircraft, such as the Concorde, reverse thrust could be used to increase the rate of descent.

Other accidents have occurred when the reverse thrust mechanism failed to retract properly following a go-around decision. An example is Pacific Western Flight 314 in February 1978.

To avoid such accidents, the deployment of thrust reversers may be governed by the thrust levers being at idle and by the compression of the squat switches which detect pressure on the wheels, indicating that the aircraft is on the runway. Even this type of protection can cause problems: in at least one case reverse thrust could not be deployed unless there was both pressure on the squat switches *and* the wheels were rotating. A hydroplaning aircraft found it impossible to deploy reverse thrust when it was required, because the wheels were not rotating.

12.7 Answers to Exercises

This section provides possible answers to the exercises in this chapter.

Exercise 99

Using most aviation calculators, the humidity given by the dew point has to be ignored. Following the key strokes given in the user manual, the density altitude is found to be 2,944 ft ASL.

Using the full formula, including the humidity, the correct answer is 3,042.5 ft ASL. For practical purposes the 98.5 ft error is not likely to be consequential, but remember that it is present unless the dew point is 0°C.

Interpreting this result, Lakeville airport currently appears to the aircraft's wings, propeller and engine, to have an air density equivalent to an airport at about 3,000 ft ASL on a standard day.

Exercise 100

Using equation 12.1 and substituting the densities of the air at sea level (1.226 kg/cubic metre) and at 6,000 ft (1.024 kg/cubic metre) from figure 12.13, the power output can be calculated as

$$\begin{aligned} \text{Output power} &= \text{Rated power} \times \frac{d_1}{d_s} \\ &= 86.5 \times \frac{1.024}{1.226} \\ &= 72.2 \end{aligned}$$

The engine will produce a power of 72.2 kW (97 horsepower)—only 84% of the sea level power.

Chapter 13

Aircraft Systems

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13.1 The Electrical System

It may be useful to review the units used in electrical systems as described in section 3.12 on page 52 before reading this chapter.

Electromagnetic Induction

Electrical current, magnetic fields and movement are related in three basic ways (these are the so-called *Laws of Electromagnetic Induction*)

1. If an electrical current is passed through a wire then the wire becomes a magnet—the principle of the electromagnet.

2. If a wire is moved when it is in a magnetic field (i.e., when it is close to a magnet), then electrical current flows in it—the principle of the generator, alternator and ignition system.

3. If an electrical current flows through a wire that is in a magnetic field, then the wire moves—this is Faraday's Law and is the principle of an electric motor.

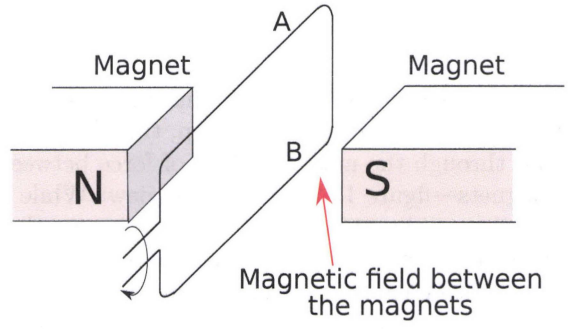

Figure 13.1: Generating Electricity

The principle of generating electricity by moving a wire in a magnetic field is illustrated in figure 13.1. In practice, as long as the wire moves through the magnetic field it doesn't matter whether:

- the magnetic field remains fixed and the wire is physically moved (as in figure 13.1)

- the wire remains fixed and the magnet is moved towards it or away from it

- the wire remains fixed and the strength of the magnetic field is changed (e.g., by using an electromagnet rather than a bar magnet).

The first of these is the basic principle of the generator, the last two the principles of an alternator.

The amount of electrical current generated by a wire moving in a magnetic field depends on the length of the wire, the strength of the magnetic field and the speed at which the wire is moved. In order to increase the length of the wire, it is wrapped into a coil, rather than being just a single loop as shown in figure 13.1.

Alternating & Direct Current

The electricity generated by the simple loop in figure 13.1 is determined by the direction in which the conductor is moving through the magnetic field.

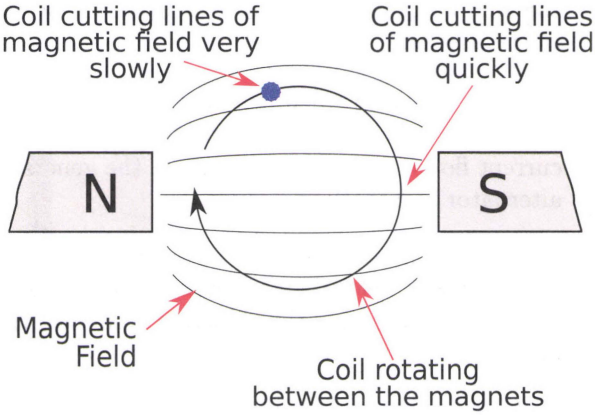

Figure 13.2: The Coil in the Magnetic Field

Consider one side of the loop, that marked A in the figure. With the rotation of the loop, this is about to descend through the magnetic lines of force between the two magnets—figure 13.2 gives a side view. While the wire is close to the "12 o'clock" position it cuts through the lines of the magnetic field much more slowly than it does at the "3 o'clock" position. This means that the electrical current being generated is not constant: it is greater at the 3 and 9 o'clock positions than at the 12 and 6 o'clock points. However, there is a further subtlety: at the 3 o'clock position the wire is *descending* through the magnetic field and in the 9 o'clock position it is *ascending*. This means that the current being generated will be in the opposite direction at the 3 and 9 o'clock positions.

In summary, a coil made like the simple loop shown in figures 13.1 and 13.2, when rotated in the magnetic field, produces no current as it passes through the 12 o'clock position, significant current as it passes through 3 o'clock, no current at 6 o'clock and significant current again *but in the opposite direction* as it passes through 9 o'clock. This is illustrated in figure 13.3. Such a current is, reasonably, called an *Alternating Current* (AC).

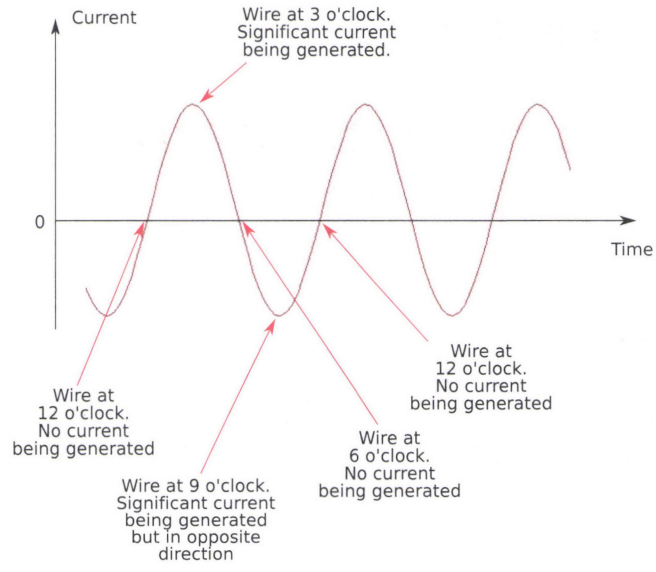

Figure 13.3: Alternating Current

In contrast to AC, current that flows only in one direction is called *Direct Current* (DC). The current from a battery is DC and, because most aircraft electronics requires DC, AC has to be *rectified* to DC for use with avionics.

13.1.1 Electrical System Components

Figure 13.5 gives a very simplified view of the electrical system of a small aircraft (based loosely on a Cessna 172M). For simplicity the ignition and starter systems have been omitted.

The main components illustrated in figure 13.5 include:

1. An engine-driven **alternator** that supplies the electricity required by the aircraft in normal flight. In older aircraft, a generator was used instead of an alternator. A generator produces direct current whereas an alternator, eponymously, produces alternating current. Generally an alternator is simpler than a generator and produces a higher voltage when the engine is turning slowly. Its disadvantage is that the electricity it generates has to be converted into direct current—a process known as *rectification*. For more details see section 13.1.2.

2. A **battery** used for starting the engine and, if the alternator fails, for feeding the aircraft's electrical systems. When the alternator is running, it charges the battery. See section 13.1.4.

3. A **regulator** that turns the alternating output voltage from the alternator into the direct current

required by the aircraft's instruments and motors. If the alternator creates too high a voltage, then the regulator lights the Over-Voltage light to warn the pilot.

4. Various **buses** (or, more strictly, *bus bars*). A bus (bar) is simply a thick strip of conductive metal used to conduct electricity from place to place; see section 13.1.3.

5. A **master switch** that can disconnect the alternator completely from the remainder of the electrical system—see section 13.1.6.

6. An **avionics master switch** that isolates the electronics bus. During engine start and stop, voltage spikes may appear on the alternator bus: this switch is used to isolate the sensitive electronic equipment from the alternator when spikes are possible.

7. An **ammeter** (a device that measures electrical current) that displays the electrical current being used to charge the battery or, if the alternator fails, the current being drained from the battery to operate the aircraft's equipment—see section 13.1.7.

8. A number of **circuit breakers** (or, less frequently, fuses) protecting the electrical components—see section 13.1.8.

13.1.2 Generator/Alternator

Unlike the aircraft's battery which simply stores and then releases electrical energy, the alternator or generator actually produces electricity, converting the kinetic energy of the engine into electrical energy.

The Generator

A modern generator typically uses a combination of permanent and electromagnets to provide the magnetic field, some of the generated electricity being used to supply the electromagnets. The aircraft's engine rotates a coil of wire in the magnetic field.

Extracting the electricity being generated is awkward because the coil is continuously rotating. The process used in a generator is illustrated in figure 13.4—the coil rotates with a commutator (a conductor divided into two parts with an insulator between them). Brushes, typically made of carbon, are held against the commutator by springs and conduct the electricity away. Strictly speaking, the current that is produced is direct because it never reverses direction, but it is not smooth: it looks like figure 13.6. Rectification is not required but smoothing is.

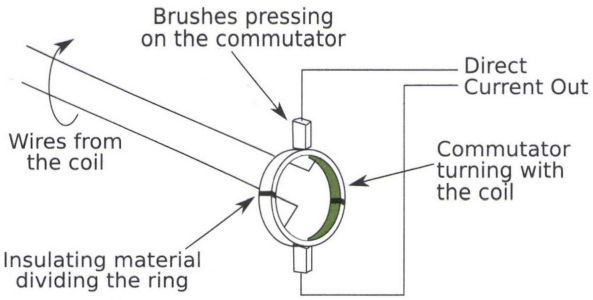

Figure 13.4: Extracting Electricity from a Generator

The Alternator

An alternator is typically lighter and smaller than a generator with the same power output, but its main advantage is that it produces its rated output voltage at much lower engine speeds.

The magnetic field in an alternator is produced by electromagnets, created by extracting a small amount of the electrical current being generated and passing it around a coil. To kick-start this process, current is needed from the battery to induce the electromagnetism—if the battery is completely flat then, in some designs, the alternator will not start producing electricity. The magnet is then moved by the rotation of the engine near to a coil of wire and electricity is thereby created. If an alternator fails and the aircraft is running on battery power, the pilot must turn off the current being drained to create the magnetic field of the (dead) alternator—some aircraft have a separate switch for this while others have a split master switch, one side of which isolates the alternator.

The electricity produced by an alternator is pure AC as illustrated in figure 13.3. An aircraft's electrical system generally requires DC for most of its devices and so a further stage, known as *rectification*, is required. This is performed by the regulator in figure 13.5.

Note that twin-engined aircraft normally have two alternators, one on each engine. Often either alternator by itself can support the electrical demands of the aircraft.

13.1.3 Bus Bars

A bus bar is simply an electrical conductor (often a piece of rigid metal) used to distribute electricity around the aircraft systems.

In the simplified electrical system in figure 13.5, electricity from the alternator is rectified to produce direct current and then feeds an alternator bus. This bus feeds the two operational buses of the aircraft: one for the equipment sensitive to voltage surges (e.g., radios) and one for less sensitive equipment (e.g., flap motors).

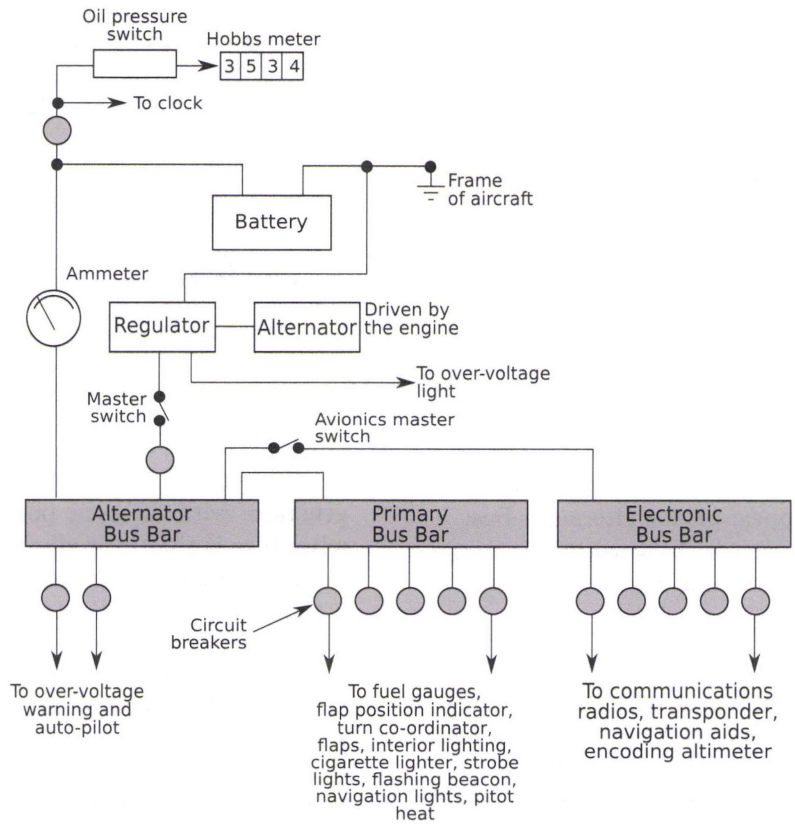

Figure 13.5: Simplified Aircraft Electrical System

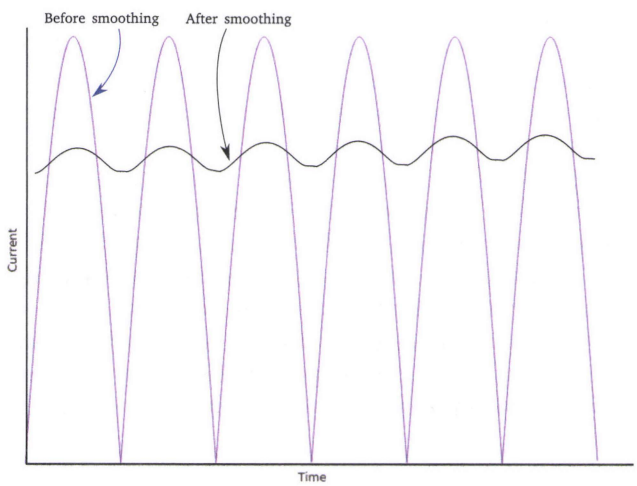

Figure 13.6: Electricity from a Generator

13.1.4 Battery

Method of Operation

Unlike an alternator or generator, a lead-acid battery of the type used in most small, general-aviation aircraft does not produce electricity—it simply stores it and releases it on demand.[1] Electricity from the alternator or generator is stored in the battery while the engine is running; the battery itself is used to drive the starter motor and to supply the aircraft electrical circuits if the alternator or generator fails. It is important to note that, unlike automobile systems, most aircraft ignition systems do not require the battery to be present for the engine to continue running—the electricity required to create the sparks is generated by the ignition system as described in section 13.2.

Although an aircraft battery stores and releases electricity in the same way as an automobile battery, it is internally quite different because of the different environment in which it has to operate: at much greater angles to the horizontal (sometimes inverted in aerobatic aircraft), at much greater extremes of temperature and at rapidly changing external atmospheric pressures.

A battery consists of a number of *lead-acid cells* each of which consists of two lead plates immersed in an electrolyte, typically a mixture of sulphuric acid and water. One plate (the positive electrode) is made of lead dioxide and the other plate (the negative electrode) is made from sponge lead—metallic lead brought to a

[1] For this reason, it is strictly not a *battery*—it's an *accumulator*. However, the term "battery" is so common that it would be pedantic not to use it in the aircraft context.

spongy form by reduction of lead salts, or by compressing finely divided lead. The maximum potential difference (voltage) that a lead/acid cell can theoretically produce is 2.041 volts. A battery therefore consists of 6 or 12 cells connected in series to give a nominal 12 or 24 volts.

When electricity is being drawn from the battery, the sulphuric acid converts both electrodes to lead sulphate, freeing electrons as it does so. These electrons create the electrical current. On charge, the lead sulphate at the positive electrode is converted back to lead dioxide (with oxygen being generated) and the lead sulphate at the negative electrode is converted back to sponge lead (with hydrogen being generated).

A battery is rated by the size of the potential difference it can generate, measured in volts, and the amount of current it can source, measured in ampère-hours.

Thus a fully charged 12V, 20 ampère-hour battery should be able to sustain a potential difference of 12 volts while sourcing 20 amps of current for an hour (or 10 amps for 2 hours, ...).

Exercise 101 *A battery consists of 6 cells and is rated at 20 ampère-hours. What is the maximum voltage it can provide? If it is completely discharged, how long will it take to charge it fully from a 12V charger rated to provide 10 amps?*

Possible answers to the exercises are given at the end of the chapter, starting on page 305.

Cold & Warm Weather Operation

Temperature is important in the operation and life of a battery. Chemical reactions take place more slowly when the battery is cold. A cold battery:

- is equivalent to a warm battery of much lower ampère-hour rating. A battery that, fully charged, will start an engine 10 times in warm weather might only be able to start it 3 times in cold weather.
- takes much longer to charge.
- must not be allowed to discharge or it might freeze: a discharged battery will freeze very easily but a fully charged one will not freeze at temperatures above $-50°C$.

On the other hand, a battery deteriorates faster in warm climates and sometimes an electrolyte with a lower specific gravity (i.e., with a lower density) has to be used to extend its life.

13.1.5 Lighting

In addition to interior lighting used to illuminate instruments and maps, most aircraft have a number of external lights. Section 605.16 (1) of the CARs states that:

> No person shall conduct a take-off in a power-driven aircraft for the purpose of night VFR flight, unless it is equipped with
>
> ...
>
> (i) a means of illumination for all of the instruments used to operate the aircraft;
>
> (j) when carrying passengers, a landing light; and
>
> (k) position and anti-collision lights that conform to the *Aircraft Equipment and Maintenance Standards.*
>
> ...
>
> No person shall operate an aircraft that is equipped with any light that may be mistaken for, or downgrade the conspicuity of, a light in the navigation light system, unless the aircraft is being operated for the purpose of aerial advertising.

Section 605.18 requires the same lighting for IFR flights.

The standard referred to in point (k) requires that the aircraft be fitted with green and red navigation lights, one or two position lights as far back on the aircraft as possible and a flashing beacon light.

The lights that may appear on an aircraft include:

Navigation lights. These are fitted near the leading edge of each wingtip and the light on the right wingtip is green and that on the left wing red. This allows a pilot of another aircraft, particularly at night, to determine the direction in which the aircraft is flying.

Position lights.[2] Most aircraft are fitted with steady white lights in various locations. Airliners often have these lights on the trailing edge of each wingtip and sometimes along the trailing edges of the horizontal tail.

Anti-Collision Beacon lights. Flashing (rotating) beacon lights may be fitted to aircraft near the center of the fuselage, either above or below or in both positions. These lights are reddish orange and are turned on just before the engines are started to warn ground personnel that the engines are operational.

Strobe lights. High-intensity strobe lights that flash a white light are located on each wingtip. Most

[2] So called because they advertise the aircraft's position.

smaller aircraft are equipped with only one of these near the leading edge just behind the red or green navigation light; airliners may be equipped with an additional strobe at the trailing edge as well.

Wing lights. Many airliners have lights along the root of the wing leading edge that can be used to illuminate the wing and engine supports in flight. These may be used to make the plane more visible during takeoff and landing or to inspect the wings for icing or damage in flight.

Taxi lights. This is a bright white light mounted to shine forward, used when the aircraft is taxiing.

Landing lights. Bright white landing lights are fitted to provide forward visibility during landing.

Runway Turnoff lights. These are usually located in the leading edge of the wing root and provide side and forward lighting during night taxiing.

Wheel Well lights. Some large aircraft are equipped with lights in the nose and main gear wheel wells. These are provided to assist during the pre-flight inspections of an aircraft at night.

In the past these lights were incandescent bulbs driven from the primary bus bar (not the Electronic Bus Bar)—see figure 13.5. Today they are increasingly light-emitting diodes which offer a longer life with reduced current drain.

13.1.6 Master/Alternator/Generator Switches

In some aircraft (for example, a Cessna 172) the master switch is divided into two: one half connects the alternator, the other the battery, to the bus. This allows the alternator to be isolated from the electrical system so that it does not continue to draw power to create its magnetic field after it has failed. In some aircraft the POH also requires that the alternator be disconnected in this way while the engine is started because, at low revolution speeds, the alternator can be stressed as it tries to reach its stable output voltage.

13.1.7 Ammeter/Load Meter

It is important to know when the aircraft is drawing electricity from the battery rather than the alternator or generator. If the alternator has failed, then the battery will only be able to sustain the electrical load for a short time and the pilot needs to switch off all non-essential electrical devices, particularly transmitters such as the transponder.

An ammeter or load meter, if included in the pilot's scan, can provide this information. It can otherwise be difficult to detect an alternator failure—gradually lights will dim but, by the time this is noticeable, there is probably insufficient time left to take action.

As shown in figure 13.5, an ammeter (a device for measuring the amount of electrical current flowing) can be used to monitor the electrical system. Aircraft ammeters are designed with the zero point in the centre. The ammeter indicates whether current is passing to the battery (i.e., the battery is being charged by the alternator or generator) or current is passing out of the battery.

Not all aircraft have ammeters—in some a warning light is fitted instead that, when illuminated, indicates that current is being drawn from the battery.

Another indicator for the operation of the electrical circuit is a load-meter. This has a scale beginning with zero and shows the load being placed on the alternator or generator. Note that the load meter and ammeter display different things:

- the ammeter displays whether the battery is being charged or not. A reading of zero is good, meaning that the battery is fully charged and the rate at which current is being drawn from it is matched by the rate at which it is being recharged.

- the load meter displays how much current is being drawn by the aircraft's electrical systems from the alternator. A reading of zero indicates either that all electrical systems in the aircraft are turned off (unlikely) or that the alternator has failed.

Anecdote 47 *Two friends of mine, both experienced pilots, were flying a Piper Cherokee back from Oshkosh, WI, to Ottawa Rockcliffe at night. While flying over the Algonquin Park, a particularly dark area, one of them noticed that the transponder light seemed dimmer than usual. They increased the brightness and made a note to get it fixed once on the ground. A little later they noticed that other displays in the cockpit, including the GPS screen, were also dimming. It took a while to realise what had happened: the alternator had failed and they were draining the battery. Once they realised this, they turned all of the electrical circuits off and realised that they might not even be able to turn on Rockcliffe's pilot-operated runway lights. Luckily they had a cellular telephone, and called a family member who knew how to turn the lights on from the ground.*

13.1.8 Circuit Breakers/Fuses

Section 605.16 (1) of the CARs states that:

> No person shall conduct a take-off in a power-driven aircraft for the purpose of night VFR flight, unless it is equipped with
>
> ...
>
> (e) in respect of every set of fuses of a particular rating that is installed on the aircraft and accessible to the pilot-in-command during flight, a number of spare fuses that is equal to at least 50 per cent of the total number of installed fuses of that rating;

Circuit breakers and fuses are weak links in an electrical circuit. Such weak links are incorporated so that, if too much current is being drawn (normally because of a faulty device or too high a voltage being applied), the fuse will blow or the circuit breaker open (pop) and thus break the circuit, preventing further damage to the devices and the possibility of fire.

Fuses are sacrificial—the wire in them melts in the presence of the high current and the fuse has to be completely replaced. Circuit breakers are reusable: they "pop" and, when the problem has been resolved, can easily be reset.

13.1.9 Grounding/Bonding

Various parts of the aircraft's electrical system (in particular the ignition system) can, if not properly grounded, generate radio frequency signals that can interfere with the avionics. This is known as Electromagnetic Interference (EMI) or *Radio Frequency Interference* (RFI).

To avoid EMI, the ground connexions of the various electrical circuits must all be connected together in a manner in which there is a very low resistance between them: creating a so-called *ground plane*. This is difficult to achieve in many aircraft because different metals are used (e.g., steel and aluminium) for different parts of the aircraft structure, and the points where these connect not only provide high resistances, they also corrode and act as rectifiers—thereby creating, rather than preventing, EMI.

Creating a good ground plane is more of an art than a science but some general rules can be applied:

- Grounding cables must have very low resistance. In particular, as the ignition circuit is a rich source of EMI, the ignition harness shielding to the magneto cap should be less than 3 milliohms.
- All surfaces that are bonded together must be clean and free of paint.
- Bonding straps, for example, between the engine and its mount, must be as short and as fat as possible to reduce their resistance (strictly *impedance*) to high frequency signals.
- All ground connexions must meet at a single point if possible.

13.2 The Ignition System

The ignition system comprises those components needed to generate the electricity that creates the spark to burn the fuel/air mixture in the engine. In the case of a reciprocating engine, where the spark is not continuous but only occurs as the piston approaches the top of the compression stroke, the ignition system must also distribute that electricity in such a way that the sparks fire at the correct time.

13.2.1 Spark Generation in Reciprocating Engines

Principle of the Magneto

The purpose of the magneto is to generate a high voltage which, when applied to the spark plug, produces the spark that ignites the fuel/air mixture. Figure 13.7 shows the gap at the end of the spark plug across which the spark jumps.

Figure 13.7: An Aviation Spark Plug (Champion Aerospace)

The magneto operates on the basis of electromagnetic induction as described on page 283. Its underlying principle is illustrated in figure 13.8 (note that this is a diagrammatic simplification): two coils, known as the primary and secondary windings, are wound around a piece of metal. The primary winding of about 200 turns has many fewer turns than the secondary which often has about 13,000. There is no electrical connexion between the primary and secondary windings.

With the contact breaker closed, a current flows around the primary coil and makes the metal core into an electromagnet, one of the principles of induction

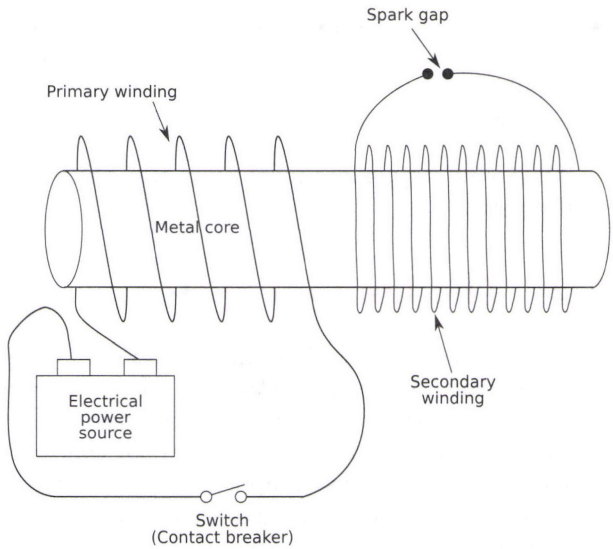

Figure 13.8: The Principle of the Magneto

being that when an electrical current is passed through a wire then a magnetic field is created.

When the contact breaker opens, the current stops flowing and the magnetic field collapses very suddenly. The secondary winding with its many turns is wrapped around the collapsing magnet and appears to be moving rapidly in a magnetic field (actually, of course, it's the strength of the magnetic field that's changing). By the laws of induction, this creates a very high voltage between the ends of the coil. It is this voltage that causes the current to jump the gap in the spark plug, creating the spark necessary to ignite the fuel/air mixture.

It would appear that a magneto allows us to generate something from nothing: a relatively small input voltage on the primary circuit results in a very high output voltage on the secondary circuit. In fact, nothing is gained: the power is calculated by multiplying the voltage by the current, and the current is much greater on the primary side than on the secondary.

A Practical Magneto

While figure 13.8 illustrates the principle of the magneto, it clearly does not represent a practical system. Figure 13.9 shows in slightly more detail how an actual magneto operates. It is very difficult to draw a magneto because, in fact, the two windings (primary and secondary) are both wrapped around the same metallic former. For clarity, in figure 13.9 the primary and secondary sides have been separated—in practice the two coils are wrapped on top of each other (although, as in figure 13.8, the insulation of the wires ensures that there is still no electrical connectivity between the two).

The main differences between the magneto in figure 13.9 and the principle illustrated in figure 13.8 are as follows:

- The electricity for the primary circuit does not come from a battery. Instead, it is generated by a simple alternator driven by the engine, rotating the primary coil in a magnetic field. This is shown symbolically in figure 13.9 by having a fixed magnetic field within which the primary coil is rotated. In practice, this magnetic field may be partially created by electro-magnets. This alternator typically supplies about 20 volts.

  The main advantage of using a magneto in an aircraft is that the ignition system becomes totally self-contained—no external electrical source such as a battery is required to keep the ignition system running.

- The circuit from the primary winding is interrupted by a contact breaker driven by a cam (a non-circular wheel) which the engine turns, thus ensuring that it opens at the correct time.

- When the cam opens the contact breaker, the magnetic field collapses very quickly and a potential difference of up to 35,000 volts is generated in the secondary windings. A capacitor (electrical storage device) is fitted across the contact breaker. This prevents a spark forming between the contact breakers as they open (called "arcing"). Arcing not only causes pitting on the contact breakers, it also reduces the speed at which the magnetic field collapses, making the magneto less effective.

- The high voltage in the secondary circuit is connected to the correct spark plug by a distributor, also rotated by the engine. By this means the electricity is routed to the correct spark plug at the correct time in the compression stroke to cause the engine to run.

- A switch is installed to short out the magneto when not in use. This is essential, because a "live" magneto can be very dangerous—it only requires someone to turn the propeller by hand to cause the magneto alternator to turn. This will generate the electricity necessary to create the sparks and start the engine. This danger is avoided by ensuring that the two sides of the primary circuit are connected when the engine is not running, normally by moving the ignition key to the *off* position. This is known as *grounding* the magneto. The wires connecting the ignition switch to the primary coils are known as P-Leads.

- The magnetos are a source of electrical interference that can affect radios and navigation devices in the

aircraft. Each magneto is therefore encased in a well-grounded metal container.

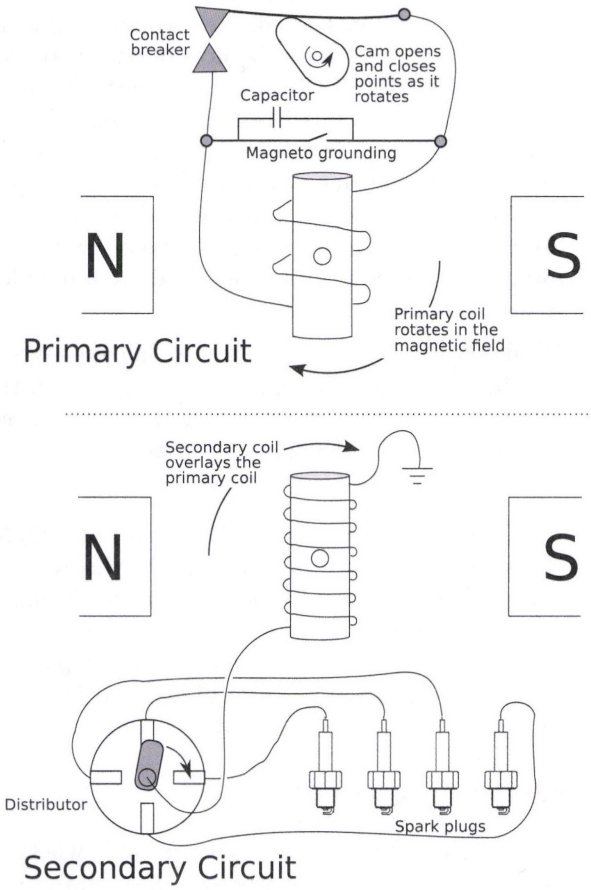

Figure 13.9: The Principle of a Real Magneto

In some light aircraft, one of the magnetos is fitted with an *impulse coupling*. This is a spring arrangement designed to make the magneto turn quickly even when the engine is turning slowly. This provides a better spark for starting and is normally indicated in the POH by requiring the engine to be started on one magneto (the one with the impulse coupling) with the second magneto only being switched in once the engine is running.

Anecdote 48 *This is the same as anecdote 1 on page 11, but with a different focus.*

I used to share the ownership of a Cessna 172 with a friend. One cold day in February, I came to use the aircraft and, following the instructions for a cold-weather start in the POH, I pulled the propeller through a few times before getting in. I was aware that pulling the propeller through would turn the magnetos and therefore potentially start the engine were the magnetos not grounded. So, I carefully checked that the ignition key was out of the ignition lock. It was.

As I pulled the propeller through it felt unusual and, realising that something was wrong, I threw myself backwards onto the ground just as the engine fired and the propeller started turning. The propeller caught and tore the sleeve of my coat and cut my hand badly—I needed stitches at the local hospital and had trouble explaining to the triage nurse how the accident had occurred. Had I been a fraction of a second later in moving away I would have likely lost at least my hand.

Later I found that, because of wear, it was possible to remove the ignition key with the magnetos still ungrounded and this is what had actually happened. My first action after leaving the hospital was to get the lock replaced so that such an incident could never happen again.

Dual Ignition

Many engines in light aircraft actually have two spark plugs in each cylinder, each driven from a separate magneto. This ensures that, if one magneto fails, the engine still continues to operate, albeit with slightly less power. During the run-up checks before a flight it is normal to check that the engine will run on each magneto individually by grounding the other as described above.

Having two spark plugs in the cylinder also creates two flame fronts (edges of burning gas) in the cylinder, thereby improving the fuel burn.

13.2.2 Fuel Ignition in Turbine Engines

The fuel in the combustion chambers of a turbine engine is ignited by taking a low voltage/high current feed from the aircraft's electrical system and using this to charge a capacitor (a device for storing electrical energy). When the voltage across the capacitor reaches a preset (high) value the energy is rapidly drained out of the capacitor and applied to an igniter plug.

Igniter plugs come in two types: an air gap plug, very similar in operation to a spark plug in a gasoline engine, and a surface discharge plug where, rather than a spark across an air gap, a flashover occurs between two parts of the plug body. Potential differences of around 25,000 volts are required for the air gap plug and potential differences of about 2,000 volts for the surface discharge plug.

If there is a flame-out in flight (i.e., the combustion extinguishes) then the engine must be restarted. This requires a significant forward speed to turn the compressor fan, and then a manual activation of the ignition system — see example 8 on page 25 where the pilots did not understand this.

13.3 The Lubricating System

13.3.1 Purposes

In both reciprocating and turbine engines there are three primary purposes of oil:

1. **Lubrication.** There are two types of lubrication: hydrodynamic and boundary. As shown in figure 13.10, *Hydrodynamic lubrication* occurs when two moving components of an engine—for example, the crankshaft in its bearing—converge and compress a film of lubricant (oil) between them. This film is normally very thin (typically a few micrometres) but, to hold the components apart and avoid metal to metal contact, it must be at least as thick as the irregularities on the surface of the components being lubricated.

   The viscosity of the oil (see section 13.3.3) is key in determining how hydrodynamic lubrication operates. If the oil is very viscous then the friction between the oil and rotating shaft will be greater but the film will be thicker. Of course, as the shaft rotates, the oil heats up and becomes less viscous.

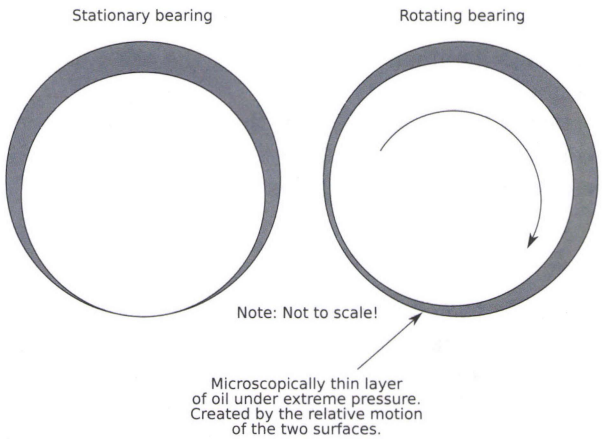

Figure 13.10: Hydrodynamic Lubrication

   Hydrodynamic lubrication is sometimes known as *fluid film lubrication* and the process is similar to that of hydroplaning on a wet runway.

   Boundary lubrication occurs in locations that need lubrication but where movement is not constant and hydrodynamic lubrication is therefore not possible. An example is the piston rings when they stop and reverse direction at top dead centre. Since it is not possible to form a compressed film of oil in these circumstances, the chemical properties of the oil when subjected to the high temperature caused by friction take effect—the constituents of the oil react with the contact surface forming a highly resistant tenacious layer (boundary film) that can support the load of separating the two elements.

2. **Cleaning.** During combustion many impurities are generated. Left unchecked, they would form a thick sludge that would block the flow of oil. Dispersants are added to the oil to cause these particles to be suspended in the oil (this is why oil looks dirty when it is drained from the engine). For example, an ashless dispersant aviation oil is designed to suspend dirt and metal particles picked up from an aircraft engine. Unless replaced, the oil will eventually become "over-suspended" and unable to extract additional impurities.

   While oil itself does not wear out, the additives do, and become depleted, and it is for this reason that oil must be changed regularly (in a reciprocating engine, typically after 25 hours if no filter is used or after 50 hours if a filter is present).

3. **Cooling.** The thin coat of oil left on the cylinder walls transfers heat from the rings to the cylinder walls, where it passes to the atmosphere through the cylinder barrel's cooling fins. Oil also absorbs heat from other sources. For example, when it passes through a turbocharger, part of the heat is absorbed by the oil and removed from the local area.

13.3.2 Types of Oil

The major distinction between types of oil is whether they are pure mineral oils or whether they contain ashless dispersant chemicals. Most engine manufacturers require that new engines be run in using mineral oil to allow the piston rings to seat themselves to the cylinder walls properly. Ashless dispersant oil, it is argued, is too good at preventing wear to allow the rings to seat properly. Pure mineral oil, on the other hand, does not prevent wear as effectively, and therefore allows seating to occur as the microscopic metal irregularities on the steel cylinder walls are worn down.

Lycoming's Service Instruction No. 1014M, for example, says: *"... All other engines must be operated on mineral oil during the first 50 hours of operation, or until oil consumption has stabilised. If an ashless dispersant oil is used in a new engine, or a newly overhauled engine, high oil consumption might possibly be experienced. The additives in some of these ashless dispersant oils may retard the break-in of the piston rings and cylinder walls."*

There are various authorities who do not accept this argument,[3] but not using mineral oil for break-in may invalidate the engine manufacturer's guarantee. There is

[3] See, for example, `http://www.swaviator.com/html/issueja02/Hangar7802.html`.

also a very strong belief within the aviation community that mineral oil must never be mixed with non-mineral oil. This again does not seem to be supported by any scientific evidence and there are numerous papers explaining that mixing causes no problems.

13.3.3 Oil Viscosity

The measurement of viscosity of oil is very confusing because there are actually two different concepts, both loosely called "viscosity":

1. **Dynamic** or **absolute viscosity** measures the resistance of the oil to shearing forces.[4] If you think of oil as being a series of layers (see figure 13.11), then its dynamic viscosity is a measure of the force that has to be applied to cause it to shear: the more viscous the oil, the more it resists shearing. The units of viscosity are *pascal seconds* but more normally millipascal seconds or *centipoises*.[5]

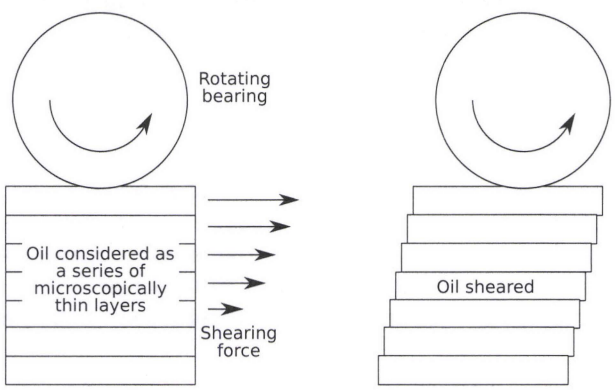

Figure 13.11: Dynamic Viscosity of Oil

2. **Kinematic viscosity** (normally represented by the symbol ν, pronounced "new"). This is the ratio of the dynamic viscosity of an oil (η, pronounced "eater") to its density (ρ, pronounced "roh"):

$$\nu = \frac{\eta}{\rho} \tag{13.1}$$

Kinematic viscosity is a measure of the resistance of the oil to flowing under gravity. It is measured by means of a capillary viscometer—basically a graduated container with a narrow tube at the bottom. If equal volumes of two oils are placed in identical capillary viscometers and allowed to flow, the more viscous oil will take longer to flow through the tube than a less viscous oil. The unit of kinematic viscosity is strictly *square metres per second* but the more commonly used unit is the square millimeter per second, also known as a centistoke.[6]

Most oils used in light aircraft are so-called *multigrade* oils. These are oils to which polymers have been added to stabilise the viscosity across a range of temperatures. The viscosity of a multigrade oil is normally quoted as two numbers:

1. The first has the suffix "W" (for "winter"—not "weight" as in some references) and represents the *dynamic* viscosity of the oil when cold.

2. The second represents the *kinematic* viscosity of the oil when hot.

Figure 13.12 gives some of the conversion factors for common oil types.

Designation	Dynamic Viscosity (centipoises)	Kinematic Viscosity (centistokes at 100°C)
10W	7,000 at −25°C	
15W	7,000 at −20°C	
20W	9,500 at −15°C	
25W	13,000 at −10°C	
20		5.6 → 9.3
30		9.3 → 12.5
40		12.5 → 16.3
50		16.3 → 21.9
60		21.9 → 26.1

Figure 13.12: Oil Viscosities

Exercise 102 *A 20W-50 oil is recommended for a particular reciprocating engine. What does this designation mean?*

13.3.4 Methods of Lubrication

An aircraft reciprocating engine typically uses either a wet-sump or dry-sump lubrication system. The difference between these is whether the oil is contained in a tank separate from the engine, or in the engine itself.

[4] A shearing force is one that acts parallel to the surface of a body rather than acting directly down on it, tending to pull the body apart in layers: think of the forces acting on the oil in the "7 o'clock" position in figure 13.10.

[5] Named after Jean Louis Poiseuille (1799-1869) who appears to have had nothing to do with the measurement of viscosity.

[6] Named after Sir George Gabriel Stokes (1819-1903) who made key advances in the field of fluid dynamics.

In a wet-sump system, the oil is located in a sump, an integral part of the engine. An oil pump draws oil from the sump and routes it through the engine before it returns to the sump. In some engines, additional lubrication is supplied by the rotation of the crankshaft which splashes oil onto portions of the engine.

In a dry-sump system, the oil is contained in a separate tank and is circulated through the engine by pumps. After the oil has passed through the engine, it is pumped from the various locations in the engine back to the oil tank by scavenge pumps. Dry sump systems allow for a greater volume of oil to be supplied to the engine, which makes them more suitable for very large reciprocating engines. They are also more applicable to engines used in aerobatic aircraft as they can provide lubrication during extended inverted flight.

13.3.5 Venting

Most reciprocating engines in light aircraft have a venting tube (or *breather tube*) to allow the pressure inside the crankcase to equalise with the outside air (the so-called *open crankcase* model). As piston rings wear with age, combustion pressure passes the pistons and enters the crankcase, forcing gases, including oil, out of the engine and into the venting tube.

In many light aircraft the venting tube simply leads to the open air and the oil is often distributed across the underside of the fuselage. This loss of oil can be avoided by fitting an *Air/Oil Separator* which, as its name suggests, recovers the oil before it passes overboard and feeds it back to the lubrication system. These devices separate the hot, oil-laden gases in a trap that collects the liquids. The dry gases are allowed to escape into the atmosphere and the oil is returned to the engine. Some manufacturers of Air/Oil separators claim that their devices capture 90% of the oil that would otherwise escape into the atmosphere.

13.3.6 Oil Dilution

In cold weather it used to be necessary to reduce the viscosity of an aircraft's lubricating oil before starting the engine, improving the flow of the oil and reducing engine wear. Nowadays, with multigrade oil available, this is not a common practice.

There are stories, possibly apocryphal, of bush pilots draining the oil from their aircraft immediately after landing in winter and keeping the oil with them in their sleeping bags or on a stove-top to keep it warm for starting the following morning.

There are several ways of reducing the cold oil's viscosity including heating it (typically with a heating pad attached to the sump) and mixing an amount of fuel into it. This latter technique is known as *oil dilution*. In general aviation aircraft, the addition of the fuel is normally a manual process. When larger aircraft used to have piston engines, oil dilution systems were built into the engines to provide a carefully measured amount of fuel.

13.3.7 Filters

An oil filter is a device placed in the oil flow between the engine and the oil tank to remove larger contaminants (slivers of metal, etc.) that could cause damage if they were to pass through the engine. For light aircraft it typically consists of a can containing a folded paper filter. As the oil passes through, some types of contaminant remain in the filter.

The filter is replaced when the oil is changed and a close inspection of the removed filter can point to problems occurring in the engine: carbon deposits may indicate that the oil has been overheated, probably because of wear on the piston rings; slivers of aluminium or steel may indicate unusual wear and point to the origin; melted aluminium globules may indicate pre-ignition or detonation.

13.3.8 Pressure Relief

The oil pressure in the engine is created by an engine-driven pump and the actual pressure increases with increased engine speed. If the pressure rises above a pre-set maximum, then a relief valve opens automatically and the excess oil is returned to the sump.

13.3.9 Oil Cooler

As its name suggests, an oil cooler is a device exposed to the external air flow through which the circulating engine oil is passed to cool it. Normally a bypass valve is fitted that causes the oil to pass through the oil cooler only if it is above a preset temperature.

13.4 The Fuel System

Fuel systems in aircraft differ widely even between light, general aviation aircraft with similar reciprocating engines. There are even wider differences between the fuel systems of reciprocating engines and turbines. This section gives some information about fuels and fuel systems in general, but for specific details you should consult the POH of any aircraft you fly.

13.4.1 Fuel Types

Types, Colours & Properties

There are three types of fuel typically used in aircraft:

1. **Mogas** (motor gasoline) is the normal gasoline fuel used in cars.

2. **Avgas** (aviation gasoline) is the fuel used in aircraft engines with spark plugs (effectively all reciprocating engines except diesels).

3. **Jet** fuel is used in turbine and diesel piston engines.

Alcohol and alcohol mixtures have been used experimentally for aircraft but are not generally available.

More details on Mogas and Avgas are given in section 12.4.13 and more details on Jet fuels are given in section 12.3.7 but the required characteristics of either are the same:

- To be "pumpable" and flow easily under all operating conditions.
- To permit engine start at all temperatures.
- To give efficient combustion in all conditions.
- To have as high a calorific value as possible (i.e., to give out the most heat from burning).
- To produce the least possible harmful effects on the engine, including the least possible corrosion.
- To provide adequate lubrication for the moving parts of the fuel system (pumps, etc.).
- To reduce fire hazards as much as possible.

Octane Rating

The Octane rating of a fuel is neither a measure of its energy content, nor the speed at which the flame created by the spark plug propagates across the cylinder. Rather it is a measure of the fuel's resistance to auto-ignition—ignition resulting from the heat of compression rather than from a spark—see section 12.4.14 on page 278.

Generally, a fuel with a high octane rating is less susceptible to ignition through compression than one with a lower octane rating.

Fuel	Density	At ...
AVGAS 100LL	0.72 kg/l (6.02 lbs/US gal)	15°C
	0.77 kg/l (6.40 lbs/US gal)	−40°C
JET A/A-1	0.81 kg/l (6.76 lbs/US gal)	15°C
JET B	0.76 kg/l (6.35 lbs/US gal)	15°C

Figure 13.13: Densities of Aviation Fuels

Density/Weight

The densities of the various forms of aviation fuel are given in figure 13.13.

Additives

Many additives are available for aircraft fuels. The purpose of these is to:

1. **reduce the chances of icing in the fuel system.** As figure 13.13 illustrates, jet fuels are denser than avgas, so water in jet fuel does not collect in the bottom of the tanks near the drains as quickly as it does with avgas. To prevent liquid water in the fuel from freezing at high altitude and clogging the fuel system, most older, turbine aircraft require that a Fuel System Icing Inhibitor (FSII) be added to the fuel during refueling. The most common FSII is Prist-brand diethylene glycol monomethyl ether (DiEGMME). This acts on any water in the fuel in the same way that radiator antifreeze does for a car—it lowers the freezing point and thereby keeps any water as a liquid rather than ice crystals.

   Transport Canada's *Service Difficulty Advisory* number AV-2008-03 issued on 28th May 2008 describes the crash of an Aero Commander 500B caused by ice forming from water in the fuel and blocking the fuel lines. The report continues *"... the amount of ice derived from as little as two droplets of water may affect most fuel injection systems. This problem can be eliminated in part by use of fuel additive icing inhibitors"*.

2. **kill fungal and microbial growth in the fuel system.** These organisms feed on hydrocarbons in the fuel and form red, brown, green or black slime that can interfere with fuel flow and quantity indications.

3. **reduce carbon deposits in turbine fuel and combustion systems.**

4. **reduce the amount of lead in avgas.** Because of the environmental concerns about burning leaded fuel, various additives have been proposed to increase the octane rating of the fuel without the use of lead. Ethyl-tertiary-butyl ester (ETBE) and anhydrous ethanol have both been proposed, but ethanol is favoured because it is completely biodegradable and is a renewable resource.

5. **reduce lead deposits in the cylinders.**

6. **prevent the oxidation of avgas.** Avgas left in an aircraft's fuel tank or an airport's fuelling system in

contact with oxygen from the air, can deteriorate and form a gum. The safe "shelf-life" of avgas is one year. Beyond that time, and particularly in a warm climate, the fuel will start to oxidise and form gum.

Contamination & Deterioration

The usual cause of fuel contamination is to fuel an aircraft designed for avgas with jet fuel. This results in extensive cylinder damage requiring complete overhaul.

Even when the correct fuel is used, contamination through water, rust, sand, dust, microbial growth or additives that are not compatible with the fuel can cause engine damage. Some of these can be removed by filters in the fuel line—see page 298—but others cannot.

Water. Aviation fuels absorb moisture from the air and always contain some water, either suspended or in liquid form. When the temperature of the fuel drops, some of the water is drawn out of suspension and falls to the bottom of the tank. Whenever the temperature of the fuel rises, new water is taken from the atmosphere to maintain a saturated solution. Changes in fuel temperature therefore result in a continuous accumulation of water. During freezing temperatures, this water may turn to ice, restricting or stopping fuel flow. This is what caused a Boeing 777 to crash short of the runway at London Heathrow on 17th January 2008 and possibly what caused a loss of engine power in a flight from Shanghai to Atlanta on 26th November 2008.

Rust. Pipes, storage tanks, fuel trucks and drums produce rust that can be carried in the fuel as small particles. Good filtration is needed to remove the rust from the fuel.

Dust and sand. Fuel may be contaminated with dust and sand through openings in storage tanks and from the use of fuel handling equipment that is not clean.

Micro-organisms. Many types of microbes are found in fuels, particularly jet fuels. These microbes (bacteria and fungi) live at the interface between the fuel and liquid water in a tank where they rapidly multiply and cause serious corrosion. They may also clog filters, screens and fuel metering equipment.

Incorrect additives. As described above, there are many additives used in fuels to improve their characteristics, particularly to inhibit their deterioration. It has been known for fuelling companies to add inappropriate additives to fuels, against the directions of the manufacturers. These can seriously harm an engine.

Of these contaminants, the most insidious is water and the way most pilots check for water in fuel tanks is shown to be inadequate by two experiments reported in the *Aircraft Fuel Control* advisory issued by the Barbados Civil Aviation Department.[7]

In one test, three gallons of water were added to the half-full fuel tank of a popular make, high wing monoplane. After several minutes, the fuel strainer (gascolator) was checked for water. It was necessary to drain 0.3 litres before any water appeared. This is much more than most pilots drain when checking for water.

In another test, simulating a tricycle geared model, one gallon of water was added to the half-full fuel tank. It was necessary to drain more than a litre of fuel before any water appeared.

In both of these tests, about 0.27 litres of water remained in the fuel tank after the belly drain and the fuel strainer had ceased to show any trace of water. This residual water could only be removed by draining the tank sumps.

Anecdote 49 *For a time I was a co-owner of a Cessna 172 that was very susceptible to water in its fuel tanks. I remember one occasion when I was performing my walk-around and found significant water in the container when I drained the fuel. This was strange because several other owners had flown the aircraft since the last rain. After a lot of experimentation we found that it required the vibration of flight (and not just shaking the wings on the ground) to cause most of the water to coalesce at the drain point.*

The fuel pumps on turbines are generally more sensitive to contaminants in fuel than those on reciprocating engines as tolerances are tighter, fuel flows are greater and fuel pressures higher. Turbine aircraft also tend to fly at higher altitudes where water freezing may plug fuel screens.

13.4.2 Fuel Management

Fuel Management—In Flight

In the air, the main fuel management issue in a large aircraft is to maintain the balance between the various fuel tanks.

In larger aircraft, if a fuel imbalance develops, a valve in the cross feed line between the left and right feeders is opened and the primary boost pumps on the side having the least fuel are shut off. This causes both engines to be supplied from the side having the more fuel until the

[7] Available from the Barbados Civil Aviation Website (`http://bcad.gov.bb/`).

imbalance is corrected. Once the fuel levels are balanced, all primary boost pumps are turned on and the cross feed valve is closed.

Many large turbine aircraft also have tank-to-tank or inter-tank transfer plumbing. Small imbalances between left and right sides can be corrected by opening the tank-to-tank transfer valve, thereby allowing gravity to move fuel from the higher to the lower side, possibly helped by the pilot putting the aircraft into a mild skid.

Anecdote 50 *When I first bought a Cessna 172 I was puzzled by the fact that the left fuel tank depleted much more quickly than the right. I joined the Cessna Pilots' Association and found that this puzzled many Cessna 150 and Cessna 172 pilots and the association had issued a* Tech Note *(number 003) describing why the imbalance occurs. It is caused by the left tank having the venting system (see figure 13.14) and therefore the greater pressure. As fuel burns from the right tank, the positive pressure in the left tank causes fuel to flow between the tanks through the connecting tube above the cabin. Thus, although most fuel is being burned from the right tank, the level of fuel in the left tank drops more rapidly. This continues until the connecting tube is no longer under fuel.*

Fuel Management—On the Ground

The storage of aircraft fuel is subject to various regulations and advisory notices. In the USA, for example, the reception, storage and dispensing of jet fuel is subject to NFPA 407 *Standard for Aircraft Fuel Servicing* and ATA Specification No. 103.[8] These indicate the conditions under which jet fuel is to be stored: only in steel tanks that have an epoxy lining suitable specifically for jet fuel service and which are:

- equipped with an access manway with internal ladder, inlet diffuser and floating suction with test cable.
- equipped with a positive sump and a manual or electric-driven sump pump to remove accumulated water. A manual water drain valve (with frost protection) must also be provided on above-ground storage tanks.
- equipped with proper venting and overfill protection and alarms.
- are correctly labelled. Jet fuel identification decals have white letters on a black background. Pipe banding of jet fuel pipelines has a single black band.

[8] Available from the National Fire Protection Association and Air Transport Association of America websites respectively.

In addition, all fuel has to be re-circulated through filtration on a regular (weekly) basis and fuel samples have to be taken while the system is pressurised (flowing) to determine its quality.

Fuel Handling—Fuelling Aircraft

The method of filling an aircraft's fuel tank varies substantially between different types of aircraft.

Many general aviation aircraft are filled from above the wing from low-pressure systems of the type found in automobile gas stations. One disadvantage of over-the-wing refuelling is the possibility of rain or other contamination of the fuel through the open fuel caps.

Most larger aircraft, with the exception of some light jets, have Single Point Pressure Refuelling systems (SPPR). SPPR connectors are usually located on the right side of the fuselage near the wing or in the leading edge of the right wing. The SPPR fitting on the end of the refuelling hose attaches by means of a positive-lock, bayonet collar to the SPPR receptacle on the aircraft. SPPR hoses usually are larger in size than over-the-wing fuel hoses and SPPR fuelling is done at higher pressures to reduce refuelling time.

Each fuelling company has standard operating procedures for fuelling aircraft from bowsers, drums or underground installations and attention is always paid to the prevention of electrostatically-induced sparks.

Grounding/Bonding

Sparks caused by static electricity are a threat during fuelling. To avoid sparks, the standard operating procedures issued by the fuelling company should be followed. These typically contain:

- A minimum period (often 30 minutes) that must elapse after the completion of filling of fuel storage tanks before hatches are opened for gauging or taking of samples. This permits the discharge of any static charges that may have been generated during filling or hauling.
- The actions to be taken to prevent static buildup during fuelling: normally grounding (earthing) the fuel truck and bonding the truck to appropriate points on the aircraft. This ensures that the fuelling truck and the aircraft have no mutual static-electrical charge.
- The inspections that need to be carried out on the grounding connections: ensuring that they are clean, unkinked and neither corroded nor coated with paint.

13.4.3 Fuel System Components

Tank Location

There are three main types of aircraft fuel tanks:

1. **Integral.** These tanks are integral parts of the aircraft's structure, sealed for fuel storage. An example of this type is the "wet wing" commonly used in larger aircraft. As these tanks are part of the aircraft's structure, they cannot be removed for service or inspection, and so inspection panels must be provided. Most large transport aircraft use this system, storing fuel in the wings or tail of the aircraft.

2. **Rigid removable.** These tanks, typically made of metal, are installed in a special compartment and may be removed for inspection, replacement or repair. The aircraft does not rely on the tank for structural integrity. These tanks are commonly found in smaller general aviation aircraft, such as the Cessna 172 or Piper Cherokee.

3. **Bladder.** These are reinforced rubber bags installed in a section of aircraft's structure to accommodate the fuel. The bladder is rolled up and installed into the compartment through the fuel filler neck or access panel. It is secured by metal buttons or snaps inside the compartment to prevent it folding up and creasing as the fuel is burned. Many high-performance light aircraft and some smaller turboprops use bladder tanks.

Venting of Fuel Tanks

As fuel is burned during flight, air must replace it in the tanks or it would eventually stop flowing. Most aircraft use outside air to vent the tanks, the vent plumbing being positioned near the highest point in the fuel system, well above the full fuel level in the tanks. Figure 13.14 illustrates the venting system on a Cessna 172.

Some aircraft, such as certain Dassault Falcons, tap off very low-pressure engine bleed air to replace the fuel volume as the level decreases in the tanks.

Whether derived from bleed air or external air, the pressurisation also helps to force as much fuel as possible to the engine, reducing the amount of unusable fuel in the system.

Baffles in Fuel Tanks

Fuel tanks, including auxiliary tanks, often have internal baffles (metal plates fitted inside the tanks) to prevent fuel from sloshing around.

Without baffles, the movement of fuel could affect the dynamic stability of the aircraft and prevent the fuel reaching the feed tanks when the fuel level was low, especially in turbulence. In "wet wing" fuel tanks the ribs (front-to-back) and spars (along the wing) provide most or all of the baffling. Holes and vents in the bottom of the ribs allow the fuel to flow by gravity to the wing transfer pumps and central feed tanks in a controlled manner.

Figure 13.14: Fuel Venting on a Cessna 172

Fuel Line—Filters/Drains

Filters are used in all stages of the manufacture, delivery, storage and use of fuel. These filters are typically made of a porous medium such as paper pleated to give a large surface area that allows the liquid fuel to pass but stops particles and water. Some fuel filters heat the fuel on entry to make the filtering process more efficient.

This type of filtering, which relies on a mechanical process to remove contaminants, is not the only possible filtering process. Other types of filtering include using clay cylinders through which the fuel passes from the outside to the hollow tube in the middle. This is not a mechanical filtering process, rather it is a chemical reaction (known as adsorption[9]) during which contaminants in the fuel adhere to the clay.

The criteria used to compare fuel filters include:

Absolute Filtration Rating: the diameter of the largest hard, spherical particle that will pass through the filter under specified test conditions. Values of about 2μm are common.

[9]Not to be confused with absorption.

Beta Ratio (β-Ratio). For a particular size of particle, this is the ratio of the number of particles in a given amount of fuel upstream from the filter to the number downstream of the filter under test conditions.

Effective Area: the total area of the filter medium exposed to the fuel flow.

Media Migration: the amount of contamination from the filter medium itself released into the "filtered" fuel.

Permeability: the relationship of flow per unit area to differential pressure across the filter medium. This is a measure of how much the filter impedes the flow of the fuel.

Induction Manifold

The induction, or *intake*, manifold lies between the throttle valve and the cylinders. In carburetted systems it is the path along which the fuel/air mixture flows and in fuel-injected systems it is the point when fuel is injected.

Fuel Heater

Fuel heaters are used to remove ice from the fuel, particularly in turbine engines, thus preventing ice crystals from blocking the fuel lines. A typical fuel heater works by using heat from the engine's lubricating oil to heat the engine-bound fuel to the optimal temperature range (21° C to 32° C) as measured at the fuel outlet port of the fuel heater.

13.5 Miscellaneous Systems

13.5.1 The Autopilot

Types of Autopilot

The autopilot, historically called "George", is a device to take some of the workload of flying an aircraft off the human pilot. The Sperry Corporation developed the first autopilot in 1912 by connecting a heading indicator and an attitude indicator to the aircraft's elevator and rudder. This was what has subsequently become known as a single-axis autopilot or "wings-leveler"—it controls roll to ensure that the aircraft flies straight and level without the pilot having to touch the controls.

Autopilots are classified according to the number of axes they control. In addition to the single-axis type, there are also two-axis devices, which also control pitch, and three-axis devices, which also control yaw. Single- and two-axis autopilots are normally found in light aircraft, while most airliners have three-axis systems.

Flight Directors & Autopilots

Flight directors are often confused with autopilots, but they are completely different devices. The pilot feeds the flight director with information about the required heading and altitude, and the flight director calculates, and displays, the best way of achieving that goal. The display is normally overlaid on the attitude indicator as track bars that the (auto)pilot needs to keep aligned with the actual path of the aircraft; see figure 13.15 where the aircraft is more nose-down than it ought to be.

Figure 13.15: A Flight Director

A pilot could manually follow the computed path or, if coupled, the autopilot could make the necessary changes to the control surfaces to follow the calculated trajectory.

The localiser and glideslope needles can be seen as a simple form of flight director because they provide the pilot with a visual representation of how to fly an ILS approach accurately.

The flight director is a calculation device; the autopilot actually flies the aircraft by moving the control surfaces. Many aircraft have flight directors without autopilots.

Problems with Autopilots & Flight Directors

The crash of the Airbus 320 described on page 22 illustrates the human error aspect of autopilots and flight directors. There are many other incidents where pilots have misprogrammed or misunderstood the flight director and thereby given the wrong commands to the autopilot.

For example, the Transportation Safety Board's report A04W0032 describes a Boeing 737 landing beside, rather than on, the runway at Edmonton. One finding was that the pilots had not set the autopilot to approach mode, which would have made it more sensitive as it tracked the localiser. The TSB report also points out

that neither pilot had slept in the 24 hours before the accident.

TSB report A04O0020 describes a Boeing 767 almost stalling as it departed Toronto because of a confusion between the autopilot mode and the flight director programming. The pilot initially did not notice the autopilot warning that it could not achieve the climb profile required by the flight director. Given that warning, the pilot should have turned the autopilot off and taken manual control.

In addition to these human factors errors, there are conditions in which an autopilot can mask the situation in which the aircraft finds itself. One example is when icing is encountered: as ice builds on the aircraft, the autopilot will compensate for as long as it can, and then switch off and hand the aircraft back to the human pilot when no more compensation is possible. Following a similar report from the FAA, the TSB report A05C0187 recommends that, whenever ice is encountered in a Cessna 208, the autopilot be immediately turned off and the aircraft be flown manually.

Anecdote 51 *There is another problem associated with autopilots: the loss of manual skills. I was once asked to sit in the right seat of a light aircraft while the pilot flew some ILS approaches. On the first approach, the autopilot tracked the localiser perfectly. We overshot and tried the same approach again, this time with the aircraft being flown manually. We would have been lucky to have landed inside the airport perimeter, and the tower called to ask where we were going. If that pilot had needed to fly a low approach without the autopilot, an accident would almost certainly have resulted.*

It is also recommended for many aircraft that the autopilot be switched off in turbulent air to prevent damage to the airframe as the autopilot tries to maintain altitude.

13.5.2 The Hydraulic System

There are many situations in an aircraft's control system when a force has to be applied remotely—to move flaps, ailerons, rudder, elevator, spoilers, cargo doors, brakes, thrust reversers, undercarriage, etc. Various mechanisms can generate this remote force: an electrical circuit can cause a remote electrical motor to turn, cables can be pulled or a fluid can be compressed in a series of pipes. Each of these has its own disadvantages, but the *hydraulic* system—the use of a compressed fluid—has certain advantages:

- It can pass around corners much more easily than a cable system.
- There is no backlash: it responds immediately.
- It can be easily maintained.
- It does not present an electrical shock hazard.
- It is less of a fire hazard than an electrical circuit.
- It can be used to deliver almost unlimited force or torque.
- Unlike metal cables, it is impervious to changing temperatures.
- It may be lighter than the equivalent electrical motors.

The basic principle on which hydraulic systems work is illustrated in figure 13.16. It exploits a theory first expounded by Blaise Pascal after whom the unit of pressure, the Pascal, is named. Pascal realised that, if gravity is ignored, then a fluid placed under pressure in a vessel of any shape will exert the same pressure everywhere. This means that if the vessel consists of a series of pipes and cylinders, compressing the fluid in one location will cause a force to be applied to all other points in the system. This force can be used to move a piston in a cylinder that, in an aircraft, can cause a flying surface to move, wheels to be lowered, brake pads to be pressed against a wheel, etc.

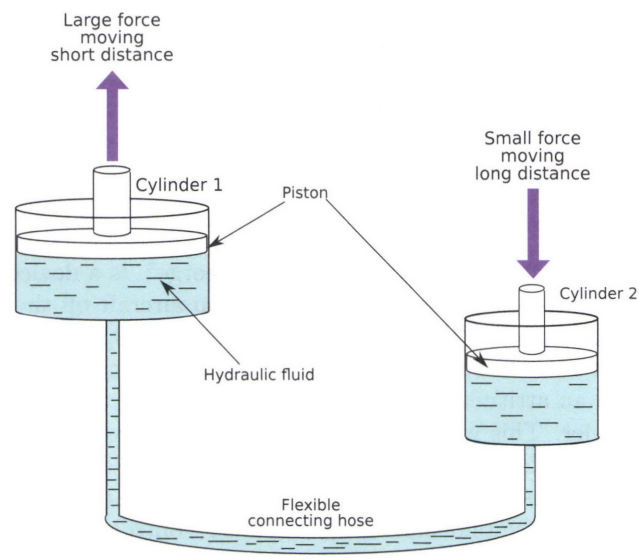

Figure 13.16: The Principle of the Hydraulic System

Consider figure 13.16. If a force is applied downwards on the piston in cylinder 2 this will increase the pressure of the liquid in cylinder 2. By Pascal's principle, the

hydraulic fluid will transmit the pressure to cylinder 1 where it will act as a force upwards on that piston.

Notice that the piston in cylinder 1 is drawn with a larger surface area than that of cylinder 2. Assume that it has a surface area of 0.003 square metres whereas the piston in cylinder 2 has an area of 0.001 square metres. If the piston in cylinder 2 is pressed down with a force of 100 newtons then it will create a pressure of 100 newtons per 0.001 square metres or 100,000 newtons per square metre[10] on the fluid. Pascal's principle says that the pressure of the hydraulic fluid will be the same in cylinders 1 and 2 and so a pressure of 100,000 newtons per square metre will be exerted upwards on piston 1. This piston has an area of 0.003 square metres so it will receive a force of $0.003 \times 100000 = 300$ newtons.

This seems to be too good to be true. By simply juggling the sizes of the pistons we can convert a 100 newton force at one point in the aircraft into a 300 newton force at another point. In fact there is a catch: to move piston 1 one centimetre, piston 2 must be moved three centimetres.

It is this tradeoff that characterises a hydraulic system: by moving a small piston a long way with a small force, a larger piston somewhere else in the aircraft can be moved a short way and exert a large force.

When operating within an aircraft, the increase in pressure at one point in the system can be created by direct pilot action (e.g., pushing on a brake pedal and thereby moving the brake pads onto the wheel) or by an engine- or electrically-driven pump.

Although the hydraulic system has advantages over electrical and mechanical systems, it also suffers from disadvantages:

- The hoses connecting the various parts of the hydraulic system must be regularly inspected and kept in good repair because a leak at any point will reduce the pressure in the whole system. Because they need to withstand high internal pressures, the hoses tend to be heavy and bulky. The wheels-up landing in dialogue 2 on page 342 occurred because the pilots did not move the hydraulic system to high pressure—during flight it was kept at low pressure to avoid putting stress on the hoses.

  Modern fly-by-wire and fly-by-optics aircraft are replacing long hydraulic hoses with an electrical or optical circuit from the flight computers to small, electrically-driven hydraulic systems close to the surfaces to be moved.

- Under certain conditions (particularly very high speeds of fluid movement and sharp bends in the hydraulic hoses) cavitation can occur—bubbles of gas forming in the hydraulic fluid. Since gas is much more compressible than liquid, this prevents the pressure from being transmitted to parts of the system.

Because of the possibility of failure, most aircraft have their hydraulic systems duplicated. For example, in some light aircraft with retractable gear, hand hydraulic pumps are provided to lower the landing gear should the main system fail. Some aircraft (e.g., Airbus 320 and Boeing 777) have a small propeller that may be extended beneath the aircraft to power the hydraulics (and part of the electrical system) in the event of an emergency. This propeller is called a *Ram Air Turbine* (RAT). The Airbus A380 has the largest RAT propeller in the world (1.63 m in diameter), but 80 cm is more common. A typical large RAT on a commercial aircraft produces from 5 to 70 kW.

In the well-known "Gimli Glider" incident on 23rd July 1983, when Air Canada Flight 143, a Boeing 767-200, ran out of fuel at 41,000 ft, the RAT was deployed to provide hydraulic pressure during the engine-out descent. As the aircraft slowed for landing, the RAT slowed and became less effective, reducing the pilots' ability to control the aircraft.

13.5.3 The Oxygen System

If the oxygen saturation level in a person's blood stream drops below about 91%, the ability to think clearly and react to changing events diminishes. This condition is known as hypoxia and it has a number of causes—see section 2.2.1 on page 33.

Oxygen Systems in Unpressurised Aircraft

In order to prevent hypoxia, various types of oxygen equipment are common in unpressurised general aviation aircraft. All of these contain a steel, aluminium or composite tank of oxygen. The tank pressure is usually about 15 Mega-pascals and regulators are used to reduce this to a level suitable for breathing and to hold the output at that pressure as the pressure in the tank drops.

There are three major types of general aviation oxygen systems:

1. **Constant Flow Systems.** This is the simplest system—the regulator ensures that oxygen at the same pressure is presented to the pilot whatever the outside air pressure and whatever the pressure in the tank. Most portable systems, as well as those built into the aircraft, are of this type.

   The disadvantage of the constant flow system is that oxygen is wasted at lower altitudes. The system

[10] Known as 100,000 pascals.

typically provides the pilot a flow of 2.5 litres per minute which is correct for flight at 25,000 ft. However, if the aircraft is only at 15,000 ft, only 1.5 litres per minute are required. The excess oxygen has no serious medical effect other than drying out the pilot's nose, but it is costly.

2. **Altitude Adjustable Systems.** This type is similar to the constant flow system except there is an adjustable control to set the flow rate to that suitable for a particular altitude. This results in a significant saving in oxygen but the system is not common except amongst some portable oxygen systems.

   The main disadvantage of this type of system is that it is not possible to adjust the flow of oxygen to each of the breathing devices individually and not all people require the same amount of oxygen (for example, a smoker requires more).

3. **Altitude Compensating Systems.** This system is similar to the altitude adjustable systems except that the adjustment is made automatically rather than manually. Beechcraft and Mooney use this type of system for their built-in oxygen.

   The main disadvantage of this system is again its inability to handle individual needs. As explained in chapter 2, different people require different amounts of oxygen at different altitudes.

Given the legal requirement to use supplemental oxygen above 10,000 ft in an unpressurised aircraft, there are effectively two ways of having it administered—by wearing a mask or by using a cannula. Many pilots, particularly those with facial hair, find masks very uncomfortable and use cannulæ instead: tubes that clip below the nose and dispense oxygen into the stream of air being breathed in.

Oxygen Systems in Pressurised Aircraft

Pressurised commercial aircraft normally ensure a cabin pressure equivalent to 8,000 ft ASL or below. If, as a result of depressurisation, the cabin altitude rises to about 14,000 ft, oxygen masks drop automatically for passengers and cabin crew (flight crew have their own masks). One of two types of oxygen-generating systems are used in these aircraft:

1. A *gaseous manifold system* that connects all oxygen masks to a central oxygen supply, usually in the cargo hold. Pulling down on an oxygen mask starts the supply for that mask only. The entire system can usually be reset by the flight or cabin crew.
2. A *chemical oxygen generator system* connected to all masks in the compartment. Pulling down on one oxygen mask removes the firing pin of the generator igniting a mixture of sodium chlorate and iron powder, opening the oxygen supply for all the masks in the compartment. Oxygen production cannot be shut off once a mask is pulled and typically lasts for 12-15 minutes. During the production of oxygen, the generator becomes extremely hot and a burning smell may be noted, causing alarm among passengers.

Neither of these two systems is intended for long-term use by passengers and, if depressurisation occurs, the aircraft has to descend rapidly to below 10,000 ft ASL.

It is claimed that there is no reliable report of a passenger's life ever having been saved by the presence of an oxygen mask of this type, or a passenger's life having been lost through not having an oxygen mask. However, the emergency oxygen system itself has in the past warned flight crews of a depressurisation. In 2000, a Ryanair Boeing 737-800 suffered a slow decompression and the flight crew was not aware of problem until the passenger oxygen mask deployment alert light came on.

13.5.4 The Vacuum System

As described in chapter 10, the operation of several of the flight instruments relies on a supply of air at a pressure lower than atmospheric. It is important to note that these instruments are not looking for a vacuum *per se*, just for a flow of air from a higher to a lower pressure.

Figure 9.4 on page 169 illustrates what is probably the simplest method of generating low-pressure air in an aircraft: a venturi is fitted to the outside of the aircraft and, by Bernoulli's Principle (see section 9.2.5) the air passing through the venturi drops in pressure. This lower pressure is piped to the instruments. The major problem with this type of vacuum generation is that it does not work until the aircraft is moving through the air—it is not possible to run up the vacuum instruments before the takeoff roll.

Rather than an external venturi, most light aircraft have a vacuum pump fitted to the engine. These come in two kinds: wet and dry.[11] Generally dry pumps are lighter and substantially cheaper than wet ones, but fail more frequently. In 1987, the FAA in the USA said that *"[dry] pumps fail catastrophically, without warning, and there is no degradation of performance obvious to the pilot to warn him of imminent failure."* The quoted life expectancy of a dry vacuum pump is typically about 500 hours whereas wet pumps typically come with a 2,000 hour guarantee.

[11] The terms refer to whether the pump is lubricated with oil (wet) or not (dry).

A dry pump typically contains graphite blades that rotate in an elliptical cylinder to produce the vacuum. The positive side of this design is that graphite is an excellent lubricant and, in this case, self-lubricates the pump. The negative side is that the graphite degrades in the presence of solvent contamination, is easily broken if a foreign object (such as a fragment of the rubber connecting hose) is ingested, and cannot handle rapid engine acceleration or reverse propeller rotation (e.g., when pulling through by hand) without damage.

Given the known failings of dry vacuum pumps, their popularity may be surprising, but they are *much* cheaper than their wet counterparts. A type of vacuum pump new to aircraft although used for many years in stationary vacuum systems has recently emerged—the dry piston air pump. This has a life expectancy of about 2,000 hours, comparable with wet pumps, but a price about half-way between those of the dry and wet pumps.

Note that while producing a low pressure on one side, vacuum pumps also blow air out at a higher than ambient pressure on the other side. This is often used for inflating de-icing boots or in other places where high pressure air is required.

In addition to these primary vacuum systems, several backup systems are marketed, particularly for light aircraft. These often make use of the reduced pressure in the intake manifold of a reciprocating engine, but their main drawback is that they only generate a high level of vacuum when the engine is idling. As a complement to a venturi system they work well because the engine is idling at exactly the time when there is no air flowing through the venturi.

13.5.5 The Pressurisation System

As described in section 2.2.1 on page 33, the human body is adversely affected by flight above about 10,000 ft ASL. Above that altitude the pilot and passengers must be supplied with oxygen or the aircraft must be pressurised to simulate a lower altitude.

The Boeing 307 Stratoliner was the first aircraft to be fitted with a pressurised cabin. This model entered production in 1940 although very few were produced. The pressurisation allowed the aircraft to fly its crew and 33 passengers at altitudes of up to 20,000 ft ASL.

The principle of pressurisation is simple: seal the cabin of the aircraft and pump air into it to keep the pressure equivalent to about 8,000 ft ASL. The practice is much harder—the pressure difference of about 5,255 kPa (7.5-8 psi) between the inside and outside of the cabin places a significant load on the structure of the aircraft and even a pin-hole through the cabin wall can allow air to escape at greater than the speed of sound. Additionally, the pressurisation/depressurisation cycle causes stress on the fuselage and metal fatigue.

There is also the problem of generating the higher-pressure air. The traditional method is bleed air extraction from the engine but this reduces the efficiency of the engine. Some aircraft, such as the Boeing 787, use electric compressors to provide pressurisation instead. It is estimated that the pressurisation of the outside air for ventilation adds up to 2% to fuel costs.

Because of the structural stress caused by the internal and external pressures, it is also essential to have a relief valve that prevents the pressure difference becoming too great. If, for example, due to a failure in the pressurisation system, the internal pressure were to be maintained at sea level on a flight at 35,000 ft, the pressure differential would be 60 kPa (9 psi), reducing the structural life of the fuselage.

Pressurisation is standard on most commercial airliners but is also available for many general aviation aircraft. However, the additional weight and cost of adding antennæ and other items that penetrate the pressurised hull are often prohibitive.

13.5.6 The De-/Anti-Icing System

Anti-icing is the process of preventing ice from forming on a surface, *de-icing* is the process of removing it once it has formed. There are different types of ice that can form on an aircraft on the ground or in flight—see section 4.14 on page 86.

Ice on flying surfaces can be one of the most dangerous conditions on an aircraft. Ice building on a flying surface such as a wing or tailplane can cause the smooth flow of air over the surface to become turbulent, reducing lift. Ice building in hinged surfaces can prevent those surfaces from moving. Ice building on windows can significantly reduce visibility. Ice building on air intakes can cause an engine to stop.

In the USA between 1990 and 2000, 12% of weather-related aircraft accidents were caused by ice. Of these, 52% were caused by induction icing (see section 12.4.11), 40% by structural icing and 8% by icing that accumulated while the aircraft was on the ground.[12] It is salutary to note that 64% of all icing-related accidents happened to single-engine, non-retractable, light aircraft.

Anecdote 52 *I was flying circuits with a pre-solo student one winter day when the temperature was about −10° C. The sky was clear and icing was not something about which I was particularly concerned. About half-way along the downwind leg, steam was issuing from a manufacturing plant, but it was thin steam, unlikely to reduce visibility seriously and, if it did, only*

[12] Source: AOPA Safety Advisor, Weather No. 1.

for 4 or 5 seconds. We flew into the steam and it immediately froze across the windshield, blocking any forward visibility.

If necessary, I could have slipped the aircraft to the runway, looking out of the side window, but although the windshield heater in a Cessna 172 is not very effective, we did manage to melt a very small hole that allowed the student to carry out the landing.

I learned a lot from this lesson (and I hope the student did)—it does not take long to pick up sufficient icing to obliterate forward visibility completely.

Anti-Icing

Anti-icing is normally achieved on the ground by coating the flying surfaces of the aircraft with a specially-prepared fluid. These fluids normally contain ethylene glycol, propylene glycol, Grade B Isopropyl alcohol, urea, sodium acetate, potassium acetate, sodium formate or chloride salts, none of which are particularly kind to the environment. Transport Canada itself (in its publication TP 13832[13]) says that "The effectiveness of anti-icing fluid in protecting aircraft surfaces from the hazardous effects of contamination by frost, snow, or freezing precipitation is a complex and poorly understood topic."

In the air, heat or fluid may be used to prevent ice build up. Propellers normally start to collect ice before wings and can be protected by having their leading edge heated or by having anti-icing fluid leaked across them. Hot air can be directed from the engine to prevent ice building up around air intakes. Other essential items such as pitot tubes, stall vanes and temperature probes are typically protected by small electrical heaters.

Section 605.15 (1) of the CARs specifies that "a means of preventing malfunction caused by icing for each airspeed indicating system" is required for VFR Over-the-Top flight. Section 704.69 further requires that, for transport category aircraft, an indicator be fitted in the cockpit to notify the pilot should the pitot heat fail.

De-Icing

Many of the techniques (e.g., applying fluids and redirecting engine heat) used for anti-icing can also be used for de-icing.

In addition there are particular de-icing techniques such as:

- inflatable "boots" on the leading edges of flying surfaces: see figure 13.17 which shows the de-icing boot on the leading edge of a Piper Aztec's horizontal tail. Inflated by air pressure, these expand, breaking off the ice that has adhered to them. It is essential to ensure that a sufficient depth of ice has built up before inflating the boots to prevent them simply pushing the ice out and allowing it to reform at the boots' extended position (a cocoon).
- electromagnetic coils fitted under the skin of the flying surface. In flight, electrical currents are passed through these to create mechanical impulses on the surface where ice has formed. This technique can be used to shed ice as thin as 1.5 mm.

Figure 13.17: De-Icing Boot on the Horizontal Tail of a Piper Aztec

While it is not an approved technique, in his classic book *Fate is the Hunter*, Ernest Gann describes his captain deliberately causing the engines on their DC-2 to backfire so that the force of the hot air blew away the ice building over their engines' air intakes. As he says, *"This is a terrible abuse of the engines, but not as bad as asking them to fly through a mountain."*

13.5.7 The Environmental Systems

The environmental system of an aircraft provides a miscellaneous set of services for the crew and passengers:

Air supply: providing a flow of breathable and healthy air to passengers. Many airliners use recirculated air for ventilation of the passenger cabin with recirculation proportions as high as 80%. Each passenger requires at least 7 litres per second of outside air, whether or not some of the air is recycled.

The major issue associated with recycled air is disease control. Air is filtered before being mixed with outside air for return to the passenger cabin. However, the efficiency of the filters used for this purpose varies with airline and national regulator policy. The European Union, for example, has

[13] Available from the Transport Canada website.

several standards ranging from requiring the removal of 90% of 0.5 μm diameter particles to 99.97% of 0.3 μm diameter particles.

Thermal control: ensuring that the cabin is kept at a standard, and comfortable, temperature. External air temperatures can vary from perhaps 35°C on the ground at a tropical airport to −50°C at cruising altitude but the cabin temperature needs to be kept constant. This is achieved by bleeding hot air from the engine and using it to drive an air conditioning unit.

Humidity control: in most airliners the humidity in the cabin is kept very low (typically between 5% and 15% relative humidity depending on the position within the cabin) to avoid corrosion of the metal of the fuselage and condensation on electronics. This low humidity can cause discomfort to passengers such as sore eyes, dry skin and drying out of mucous membranes. The latest generation of composite airliners, starting with the Boeing 787, are less sensitive to corrosion and humidity levels are higher, providing greater passenger comfort. The increased humidity comes from preserving the humidity from the passengers' breath, rather than from artificial humidifiers.

Cabin pressurisation: see section 13.5.5.

Avionics cooling. Because avionics generate heat and because the cooler they are run, the longer their life, it is important to provide cooling for avionics. The standard applied to airliner avionics is known as ARINC-600. As well as defining the sizes of avionics modules (to allow interchangeability), it also requires that an airliner's avionics be able to operate for 90 minutes following the failure of the cooling system. This is intended to allow an aircraft with a failed cooling system to be flown to a repair facility.

Actual cooling mechanisms vary between aircraft, with many military aircraft using metal rods or even liquids to conduct heat away to the outside air. In civil airliners and general aviation aircraft, fans are typically used to force air at ambient temperature through the avionics stack.

Smoke detection. Fire in flight has caused many aircraft crashes and its early detection is essential. Detectors are normally fitted in the cargo holds and passenger cabins of airliners to alert the pilot to the presence of smoke. There are two primary types of smoke detector, each with its own advantages and disadvantages:

1. *photoelectric devices* detecting the scattering of a light beam by smoke particles in the air. The challenge with these devices is distinguishing smoke particles from dust, insects and moisture, so as to avoid false alarms.[14]
2. *ionisation devices* of the type often used in household smoke detectors.

The photoelectric devices primarily detect smouldering fires, the ionisation ones, flaming fires.

Anecdote 53 *The possibility of a fire in flight is frightening, even in a small, general aviation aircraft. I fly with a portable smoke hood at hand. These are readily and cheaply available from pilot supply shops and consist of a plastic bag which the pilot places over his or her head (to keep smoke out of the eyes) and a tube filled with charcoal which fits into the mouth for breathing. I have luckily never had to use one, but feel that even a primitive device such as this might give me 3 or 4 more minutes of control of the aircraft in the event of a fire, and those few minutes might be critical.*

Fire suppression. Once a fire has been detected in flight, it needs to be suppressed. This is particularly the case with fires in the cargo hold where hand-held fire extinguishers cannot be used. Traditionally Halon 1301 has been released into the hold to suppress a fire. Water spray systems have been used for some time to prevent fires (particularly fuel fires) after a crash and—as Halon 1301 is no longer being produced because of its effect on the ozone layer—are being considered as an alternative agent for suppressing in-flight fires. The two systems suppress the fire by using different techniques: halon systems remove the oxygen needed for combustion whereas the water spray systems reduce the temperature of the combustible substances. With halon systems the fire is extinguished; with water-spray systems the materials continue to burn but at a much lower temperature and with less risk of the fire spreading to surrounding areas.

13.6 Answers to Exercises

Exercise 101

Each cell in a lead-acid battery provides a nominal 2V. This is therefore a 12V battery. Its full charge is 20 ampère-hours so, since it only stores electricity (rather than creating it), it will take 20 ampère-hours to charge it. At 10 amps this will require 2 hours.

[14] It is estimated in some research that there are 100 false alarms in aircraft smoke detection systems for each genuine one.

Exercise 102

The 20W (winter) indicates (see figure 13.12) that, in a cold engine, the oil will have a dynamic viscosity of no more than 9,500 millipascal seconds (centipoises) even if its temperature drops to $-15°C$.

The 50 indicates that the kinematic viscosity will be in the range 16.3 – 21.9 square millimetres per second (centistokes) at 100°C.

Chapter 14

Air Law

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This chapter does not merely list the contents of each section of the Canadian Aviation Regulations (CARs) with which you need to be familiar—instead it should be thought of as a guide to use while you are reading the CARs themselves. Certainly nothing given here should be considered a legal interpretation—it is simply a practical introduction to the various sections of the CARs for everyday use and examination purposes. You need to have access to the CARs[1] and to refer to it as you read this chapter. By use of the search function, together with the basic understanding of the structure of the CARs given here, you may narrow down a search for a particularly elusive regulation.

The following sections address only those parts of the CARs that are listed on the syllabus for the Commercial Pilot written examination. In particular, where a regulation covers fixed-wing, powered aircraft and also gliders, helicopters and balloons, only those sections related to fixed-wing, powered aircraft are covered. Similarly, except in a few instances where the rules are important to commercial pilots, IFR regulations are not covered.

14.1 The Aeronautics Act

The law underlying all civil aviation regulations in Canada is the *Aeronautics Act*. This defines such terms

[1] From `http://www.tc.gc.ca/eng/acts-regulations/regulations-sor96-433.htm`

as *aerodrome*, *aircraft*, *commercial air service* and *pilot-in-command* and provides the Minister of Transport with the authority to define further rules: the CARs.

Exam Hint 29 *When studying for the air law part of the Commercial Pilot Licence examination, a good place to start is to review the questions from the PSTAR examination. These are available from Transport Canada's Internet site and, while the commercial syllabus includes a great deal more than is covered by the PSTAR, the PSTAR provides a good grounding.*

The parts of the Aeronautics Act particularly relevant for those studying for a Commercial Pilot Licence include the following:

- Section 3: The definitions of *aerodromes, registered aerodromes* and *certified aerodromes.* The Transport Canada written examination requires that pilots understand the difference between these definitions. An aerodrome is *"any area of land, water (including the frozen surface thereof) or other supporting surface used, designed, prepared, equipped or set apart for use either in whole or in part for the arrival, departure, movement or servicing of aircraft and includes any buildings, installations and equipment situated thereon or associated therewith."* This is clearly a very broad definition of aerodrome including the field at the back of a house used as a runway for an ultralight and also Vancouver International Airport. An aerodrome may be *registered* or *certified.* A certified aerodrome is also termed an *airport.*
- The Aeronautics Act applies even outside Canadian airspace: *"Every person who commits an act or omission outside Canada that if committed in Canada would be a contravention of a provision under this Part shall be deemed to have committed a contravention of the provision under this Part and may be proceeded against and punished in the place in Canada where the person is found as if the contravention had been committed in that place."*
- Section 6.5 (2): *"The holder of a Canadian aviation document that imposes standards of medical or optometric fitness shall, prior to any medical or optometric examination of his or her person by a physician or optometrist, advise the physician or optometrist that he or she is the holder of such a document."* This is the requirement to tell any doctor or optometrist you consult that you are a pilot.
- Section 7: The process by which the Minister may suspend, cancel or refuse to renew a Canadian aviation document and the rights that the document holder has to appeal that decision.

The Aeronautics Act is the enabling document for the CARs. As shown in figure 14.1, these regulations expand the Aeronautics Act and themselves support standards and advisories. Compliance with the regulations and standards is compulsory whereas compliance with the advisories is, eponymously, advised. The regulations contain both "offence provisions" which define what you must, and may not, do and "administrative provisions" which place obligations on the Minister and delegated officials.

As an example of the difference between a regulation, a standard and an advisory, consider the control of wildlife on airports. *Regulation* 302.305 states that an operator of an airport must have a wildlife management plan (an offence provision), *standard* 322.305 lists the documents to be consulted when creating such a plan and *advisory* 342.305 advises airport operators on how to identify potential wildlife hazards around the airport (crops growing nearby, etc.).

The CARs became law on 10th October 1996 replacing the Air Regulations and Air Navigation Orders.

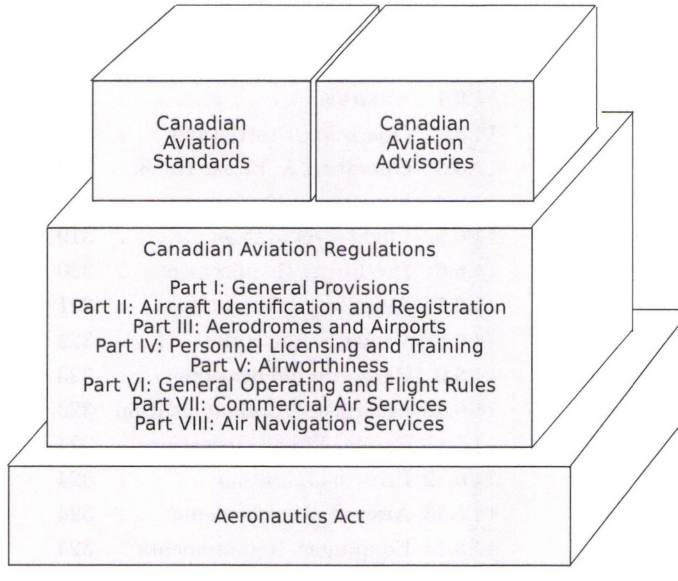

Figure 14.1: The Canadian Aviation Regulations

As illustrated in figure 14.1, the CARs are divided into eight "Parts" and the numbering of sections within the regulations, standards and advisories is, with one exception, straightforward:

- The first digit of a section number in a regulation is the number of the part, the second digit is a 0 and

the third digit is a numerical count. Thus paragraph 302 (Airports) identifies a regulation (rather than a standard or advisory) and can be found in part III of the CARs.

- A standard associated with a particular regulation has the same numbering but with the second digit being 2. Thus section 322 refers to a standard (second digit is 2) associated with the regulations given in section 302.

- An advisory associated with a particular regulation has the same numbering but with the second digit being 4. Thus section 342 (wildlife management and planning) refers to an advisory (second digit is 4) associated with the regulations given in section 302. In practice, only Part III of the regulations have associated advisories.

This neat numbering system unfortunately breaks down for part V (airworthiness) where the numbering is very different, in order to align with the numbering of the equivalent documents from the European Aviation Safety Agency (Europe) and the Federal Aviation Authority (USA).

Exercise 103 *You consult section 323 of the CARs. Is this a regulation, standard or advisory?*

Answers to the exercises in this chapter are included in section 14.11 on page 335.

14.2 CARs Part I

14.2.1 (101) Interpretation

This section contains the definition of terms used elsewhere in the CARs. The following terms are of particular importance for examination purposes:

Air Time: This is one of the two times entered into the Journey Log and represents the time from the aircraft's wheels leaving the surface until they touch again. Compare this definition with that of *flight time.*

Airport: This is defined to be an aerodrome (see above) for which a certificate has been issued.

Controlled Airspace: This is defined to be the airspace within which air traffic control service is provided. Its boundaries are defined in the *Designated Airspace Handbook.*[2] It is important to realise (particularly for IFR flights) that air traffic control services are not provided in uncontrolled airspace.

Anecdote 54 *Many years ago, as a fairly new IFR pilot, I was flying with my wife along the north shore of the St Lawrence river from Natashquan to Chevery. The clouds started to build around us and so I contacted Flight Services to file an IFR flight plan to return to Natashquan. This was no problem until I sat back waiting for my clearance. After a few minutes I realised with some shock that I was not going to get one—I was in uncontrolled airspace and I suddenly had to try to recall the ground school training I had received about flying IFR in uncontrolled airspace.*

Day or Daylight: As described in section 6.2.5 on page 117, there are various definitions of the length of the day. For aviation purposes, "day" is defined to be the time between the beginning of morning civil twilight and the end of evening civil twilight.

Elementary Work: A pilot (rather than a certified mechanic) is allowed to carry out "elementary work" on an aircraft. The precise work so classified is described in Appendix A of standard 625 of the CARs and is summarised in section 14.6.15 of this book.

ESCAT Plan: Emergency Security control of Air Traffic Plan. This is the authority under which powers can be assumed by the Canadian Government in the case of an air defence emergency. This used to be called *SCATANA* and was invoked to ground aircraft after the attacks on the World Trade Centre in the USA in September 2001.

Flight Crew Member on Call: This means a flight crew member who has to be available to report for flight duty on notice of one hour or less. This term is important when measuring duty times—see section 14.7.2.

Flight Crew Member on Standby: This means a flight crew member who has to remain at a specified location in order to be available to report for flight duty on notice of one hour or less. This term is important when measuring duty times—see section 14.7.2.

[2] Available as a pdf from the NAV CANADA publications website.

Flight Duty Time: This time, also of importance when measuring duty times, starts when a flight crew member reports for a flight or goes on standby and finishes at "engines off" at the end of the flight.

Flight Time: This starts at the moment when an aircraft first moves under its own power for the purpose of taking off until the moment it comes to rest at the end of the flight. Compare this definition with that of *air time*.

Large Aeroplane: This term refers to an aeroplane with a maximum certificated takeoff weight of more than 5,700 kg (12,566 pounds).

Minimum Equipment List: This is described in more detail in section 11.3.3 on page 236. It is a document approved by the Minister that authorises an operator to operate an aircraft with equipment that is inoperative and may specify certain equipment that *must* be operative.

Minimum Rest Period: This means a time during which a crew member has no duties, is not interrupted by the operator, and is given the opportunity to have at least 8 hours of sleep.

Minister: This refers to the Minister of Transport.

Operator: When used in the context of an aircraft, this term means the person who has possession of the aircraft as owner, lessee or otherwise.

Small Aircraft: This term refers to an aeroplane with a maximum permissible takeoff weight of 5,700 kg (12,566 pounds) or less.

Special Aviation Event: This means an air show, a low level air race, an aerobatic competition, a fly-in or a balloon festival.

14.2.2 (103) Administration & Compliance

This section of the CARs describes the obligations on an aircraft owner to make the aircraft available for inspection when required and for a pilot to make available his or her aviation documents when requested by a peace officer,[3] an immigration officer or the Minister. The *aviation documents* are defined in the Aeronautics Act as being "any licence, permit, accreditation, certificate or other document issued by the Minister . . . to or with respect to any person or in respect of any aeronautical product, aerodrome, other facility, equipment or service".

[3]The term "peace officer" is defined in the Canadian Criminal Code and includes a mayor, warden, reeve, sheriff, deputy sheriff, sheriff's officer, justice of the peace, a member of the Correctional Service of Canada, a police officer, an officer within the meaning of the Customs Act, a fishery guardian, the **pilot-in-command of an aircraft** and, under certain circumstances, members of the Canadian Forces.

14.3 CARs Part II

14.3.1 (202) Aircraft Marking & Registration

Together with the accompanying standard (section 222), this section defines the size and shape of the registration letters that must be visible on an aircraft. The registration letters consist of *CF* followed by 3 letters or *C* followed by 4 letters. If you own a non-vintage aircraft with a *CF* prefix (e.g., CF-PTN) then, when the aircraft is repainted, its identity must be changed to a single *C* prefix followed by the remaining four letters (e.g., C-FPTN). However, special arrangements can be made to preserve the original markings on vintage aircraft.

14.3.2 (202) Certificates of Registration

No one may operate an aircraft (except a hang glider or parachute) in Canada unless it has been registered in Canada or in a foreign state that has an agreement with Canada.

An aircraft may be registered in the name of any Canadian individual over the age of 15 or in the name of an incorporated company and is registered as being privately, commercially or state owned. To be registered as a state aircraft, it must be owned by and exclusively used by the government of Canada.

Anecdote 55 *I have often been a member of a group of pilots jointly owning an aircraft. It is often more convenient to form an incorporated company and have the company own the aircraft, rather than for the individual pilots to be named as owners. Incorporation allows the membership of the group to change without the need to re-register the aircraft: the incorporated company persists as the individual pilots join and leave.*

As described in section 11.1.5 on page 231, no aircraft may be flown unless the certificate of registration is on board.

14.3.3 (202) Transfer of Ownership

An aircraft's certificate of registration is cancelled when the ownership of the aircraft changes or the owner's address changes. When this occurs, an "interim registration" comes into force that lasts for three

months. During this time the new owner must apply for a new certificate.

14.3.4 (203) Operation of a Leased Aircraft

In order to fly an aircraft leased from another company, the lessor and the lessee must each hold a Canadian operator certificate for the aircraft type, the lessee must be qualified to be an owner of a Canadian aircraft, the maintenance schedule must be followed by the lessee, all crew members must be employed by the lessee and the registered owner must inform the Minister of the details of the lease, in writing, within seven days of the lease starting.

14.4 CARs Part III

14.4.1 (301) Aerodromes

This section of the CARs describes the responsibilities and duties of aerodrome operators, including the mechanism by which the operator can have the aerodrome listed in the Canada Flight Supplement. In particular the operator must allow access to Department of Transport inspectors.

This section also covers:

- the markings that an operator must install at an aerodrome: particularly the red flags or cones that must be installed along the boundary of an unserviceable movement area and the markings required to indicate runways that are closed.

- the windsock (strictly the "wind direction indicator"). Except where the direction of the wind can be determined by radio or other means such as smoke movement, the aerodrome operator must install a wind direction indicator that is of conspicuous colours, in the shape of a truncated cone; visible from an aircraft flying at an altitude of 300 m (1,000 ft) above the indicator and illuminated when the aerodrome is used at night.

- the necessary lighting if the aerodrome is to be used at night. Basically each side of the runway must be marked along its entire length with a line of fixed white lights visible in all directions from an aircraft in flight at a distance of at least two nautical miles. If this is not practical (e.g., because of a lack of electrical power) the operator may, instead, install a fixed white light at each end of the runway to indicate runway alignment and white retro-reflective markers capable of reflecting lights from an aircraft aligned with the runway centreline and visible at a distance of at least two nautical miles.

  Whether reflectors or lights are used, they must be positioned symmetrically either side of the runway, the spacing between them must not be more than 60m (200 ft) and each row must be at least 420m (1,377 ft) long and contain at least eight lights or markers.

  Taxiways used at night must be marked with parallel rows of fixed blue lights or blue retro-reflective markers placed no more than 60m (200 ft) apart.

Anecdote 56 *I am unable to remember arbitrary numbers like these: why 60m rather than 65m? Such numbers are, of course, a gift for people setting multiple-choice examination questions. The technique I employed for all of my aviation examinations was to prepare a single piece of paper containing these arbitrary numbers. I would read this through immediately before going into the examination room, would then discard the paper (it's obviously not permitted to take it in), walk into the room and immediately write down as many as I could remember on a piece of the supplied scrap paper. This is legally justifiable (no notes are being brought in) and, I believe, ethically justifiable; knowing whether the spacing of runway edge lights is at most 60m or 65m doesn't make me a better pilot. If I ever build a runway, then I'll look the spacing up in the CARs.*

- the various restrictions at an aerodrome. These include restrictions prohibiting a person from:
  - walking, standing, driving or parking a vehicle or aircraft or causing an obstruction on the movement area of an aerodrome without the permission of the operator or, where applicable, the appropriate air traffic control unit or flight service station.
  - towing or parking an aircraft on an active movement area at night unless the aircraft has operating wingtip, tail and anti-collision lights or is illuminated by lights mounted on the towing vehicle and directed at the aircraft.
  - allowing a bird or other animal to be unrestrained within the boundaries of an aerodrome except for the purpose of controlling other birds or animals at the aerodrome as permitted by the operator.

  - firing a gun within or into an aerodrome without the permission of the operator.
  - smoking or displaying an open flame on or close to an apron or in any area where smoking or the presence of an open flame is likely to create a fire hazard that could endanger persons or property.

14.4.2 (302) Airports

An airport is an aerodrome for which a certificate has been issued. Sections 302.10 and 302.11 (the only sections covered by the Commercial Pilot syllabus) basically repeat the prohibitions listed above for aerodromes in general in the context of airports.

14.5 CARs Part IV

14.5.1 (401) Permits, Licences & Ratings

This section covers the requirements for, and application of, the various flight crew permits, licences and ratings: pilot permits (including student permits), pilot licences (including airline transport pilot licences), flight engineer licences, aeroplane class ratings, aircraft type ratings, night ratings, VFR Over-The-Top ratings, instrument ratings, second officer ratings, flight instructor ratings and passenger-carrying ratings.

The major requirements of this section are the recency standards and the need to maintain personal logbooks. The recency standards are:

- to have acted as pilot-in-command or co-pilot of an aircraft within the last five years or, within the past 12 months, to have completed a flight review with a flight instructor who has checked that the pilot meets the skill requirements of the particular licence or rating.
- to have successfully completed a recurrent training programme within the last 24 months.
- when carrying a passenger other than a flight test examiner, to have completed within the last six months
  - five night or day takeoffs and landings for a day flight
  - five night takeoffs and landings for a flight wholly or partly at night.
- if flying IFR, to have passed an instrument rating flight test within the last 12 months or, within the last six months, to have six hours of instrument time and completed six instrument approaches to minima. For a flight instructor giving IFR lessons, this latter requirement can be satisfied by giving training to students who fly the six hours and the six approaches.

All flight crew must maintain personal logbooks and, for each flight, record: the date of the flight, the type of aircraft and its registration mark, the flight crew position in which the holder acted, the flight conditions (day, night, VFR, IFR), the place of departure, the place of arrival, all of the intermediate takeoffs and landings and the flight time.

14.5.2 (401) Commercial Pilot Licence—Aeroplane

This section lists the privileges that you will enjoy when having obtained a Commercial Pilot Licence. These include:

- the privileges of a private pilot licence
- the privileges of a VFR Over-The-Top rating
- the privilege of acting as pilot-in-command of a single-crew aircraft providing a commercial air service
- the privilege of acting as co-pilot of an aircraft providing a commercial air service

Perhaps the most surprising of these is the permission to fly VFR Over-The-Top. The meteorological conditions that need to exist when flying VFR Over-The-Top are contained in section 602.116 of the CARs: see section 14.6.8.

Note that a Commercial Pilot Licence does not allow you to fly your own aircraft for hire or reward, independently of a company holding an air operator certificate. As with a private pilot licence, you *may* share the direct cost of a flight (rental, oil, fuel) with passengers and *may* be reimbursed for the direct cost of a flight where it is incidental to your full-time employment, or when you are volunteering for a charitable event.

14.5.3 (404) Medical Requirements

In order to use particular aviation licences, a medical certificate is required: see figure 14.2. It is commonly believed that a medical certificate of a particular category is valid for a particular period (e.g., a category 1 certificate is valid for 6 months for a pilot over 40 years of age). Strictly, this is not the case: it is the type of licence being used that determines the expiry of the medical certificate, not the category of medical

certificate: see figure 14.2. Thus, if a 50 year-old pilot has a category 1 medical certificate, that certificate is valid for 24 months as long as the pilot only makes use of the privileges of a private pilot licence. The end of the validity period is calculated from the first day of the month following the medical examination.

The minister can extend the validity of a medical certificate for up to 60 days if a current medical certificate is still valid and the pilot can demonstrate that there has been no opportunity to have a medical examination in the 90 days before the point at which the current certificate will expire.

A medical certificate is the minimum declaration of medical fitness: it is necessary but not sufficient for acting as pilot, flight engineer or air traffic controller. Clearly leaving the doctor's office with a valid medical certificate and falling down the stairs and breaking both legs does not leave a pilot medically fit to fly. For each flight, a pilot effectively declares that he or she is medically fit. The CARs specifically state that the following conditions render a pilot unfit:

- One of the following circumstances exists and could impair the pilot's ability to exercise the privileges of the licence safely:
  - suffering from an illness, injury or disability
  - taking a drug
  - receiving medical treatment
- Have been involved in an aircraft accident that is wholly or partially the result of any of the circumstances above
- Have entered the thirtieth week of pregnancy
- Have given birth in the preceding six weeks.

Note that the first of these items requires an assessment that any medical treatment you are having would not impair your ability to exercise the privileges of your licence. The only person really capable of making that determination is, of course, your aviation medical examiner.

When you undergo a medical examination to renew your certificate, the physician is required either: to sign and date your medical certificate and stamp it with his or her official stamp indicating that you are "fit" and return the medical certificate, or to advise you that you are "unfit" and return your medical certificate unchanged.

14.5.4 (406) Flight Training Units

This section of the CARs lays out the requirements on a company wishing to provide flight training. In summary, such a company:

- has a flight training unit operator certificate, or
- has a private operator certificate or an air operator certificate specifying the aircraft used for training and the training is not for a recreational pilot permit, a private pilot licence, a commercial pilot licence or a flight instructor rating, or
- is providing training to the owner of the training aircraft or a member of his or her family, or
- is providing training to a director of a corporation that owns the training aircraft and the training is not for a recreational pilot permit or a private pilot licence, or
- is providing training using an aircraft that has been obtained from a person who is at arm's length from the flight instructor, and the training is not for a recreational pilot permit or a private pilot licence.

14.6 CARs Part VI

14.6.1 (601) Airspace

Canadian airspace is classified into the classes listed in figure 14.3. In principle, any airspace could be given any classification and the *Designated Airspace Handbook* defines the boundaries of each piece of classified airspace. In practice, the classifications are used reasonably consistently as listed in the *notes* column in figure 14.3.

The primary consideration in allocating airspace is to keep IFR traffic in controlled airspace where possible (particularly around an airport). Air Traffic Control is able to provide clearances only in controlled airspace and flying IFR in uncontrolled airspace is awkward for the pilot (although it occurs over much of Canada).

All class A, B and C airspace and some class D and E airspace is designated as *Transponder Airspace.* Aircraft may only fly in this airspace if fitted with a working mode C (altitude encoding) transponder.

Exam Hint 30 *Class E airspace confuses some students. It* ***is*** *controlled airspace, but VFR traffic does not require any type of clearance or permission to enter it. Sometimes an aerodrome with a small amount of IFR traffic has a class E control zone around it and these are often designated Mandatory Frequency zones. It is that designation, rather than the class E airspace, that makes a radio mandatory.*

Remember, however, that even though VFR traffic can freely enter class E airspace, it is *controlled airspace so the VFR visibility minima for controlled airspace apply—see section 14.6.8.*

Licence or Permit	Medical Certificate Category	Validity Period Under 40 yrs	Validity Period 40 yrs or older
Commercial Pilot	1	12 months	6 months
Airline Transport Pilot	1	12 months	6 months
Flight Engineer	1	12 months	12 months
Air Traffic Controller	1 or 2	24 months	12 months
Private Pilot	1 or 3	60 months	24 months
Student Pilot	1, 3 or 4	60 months	60 months
Recreational Pilot	1, 3 or 4	60 months	24 months

Figure 14.2: Medical Certificates

Class F airspace is designated as either *restricted* or *advisory*. VFR flight is not permitted in class F restricted airspace unless authorised by the controlling agency specified in the *Designated Airspace Handbook*. IFR flight is not permitted without an Air Traffic Control clearance or the permission of the minister. Both VFR and IFR aircraft are allowed to fly through class F advisory airspace but the pilot should take extra care in looking for other traffic.

Exercise 104 *An airway crosses directly over the town of White Lake which lies at 1,000 ft above sea level. White Lake is well away from any aerodrome and any designated airspace. What is the class of airspace at 1,800, 5,000, 10,000, 14,000 and 21,000 ft ASL above White Lake?*

14.6.2 (601) Aircraft Operating Restrictions

This section deals with miscellaneous hazards to aircraft. It prohibits over-flying forest fires below 3,000 ft AGL unless you are acting under the instruction of a fire-control agency, it requires obstacles to be lit and prohibits the shining of bright lights (in particular, lasers) at aircraft.

14.6.3 (602) Operating & Flight Rules

602.01: Reckless or Negligent Operation of Aircraft

This section prohibits you from operating an aircraft in a reckless or negligent manner that could endanger life or property.

(602.02) Fitness of Flight Crew Members

This is an interesting section because it puts the onus of responsibility to ensure that no one who is fatigued or otherwise unfit acts as a flight crew member on those operating a commercial service rather than on the flight crews themselves.

(602.03) Alcohol or Drugs—Crew Members

This section prohibits you from acting as a crew member for twelve hours after consuming alcohol, while under the influence of alcohol or while using any drug that impairs your faculties so that the safety of the aircraft is endangered. For more details of the effects of alcohol on a pilot see section 2.2.6 on page 37.

Exam Hint 31 *Most pilots are familiar with the 12 hour limit ("bottle to throttle") but many are unfamiliar with the second requirement: no influence. So if you drank 15 hours before the flight, but are still influenced by the alcohol, then you cannot fly.*

(602.04) Alcohol or Drugs—Passengers

Passengers are only allowed to consume intoxicating liquor that has been provided by the operator of the aircraft and operators are not allowed to supply intoxicating liquor to a passenger who is already impaired by alcohol. Further, an operator may not allow a passenger to board an aircraft if the passenger is sufficiently impaired by alcohol or other drug as to present a hazard to the aircraft unless the drug has been administered by a doctor and the passenger is under medical supervision.

Classification	Controlled?	Notes
A	Yes	Most high-level airspace (between 18,000 ft and FL600). VFR flight not allowed except by permission of the minister.
B	Yes	Between 12,500 and 18,000 ft if there is controlled airspace beneath. VFR flight requires a clearance from ATC.
C	Yes	Control zones or terminal control areas around large airports. VFR flight requires a clearance or prior permission from ATC.
D	Yes	Terminal control areas around large airports and control zones around medium-sized airports. VFR flight requires two-way radio communication with ATC or prior permission from ATC.
E	Yes	Airways, control zones around smaller airports and some terminal control areas, above FL600. VFR flight is unrestricted.
F Advisory		Where special activities (training, soaring, military exercises, etc. take place).
F Restricted		Where flight is prohibited (often for reasons of aircraft safety, but sometimes for reasons of privacy of items on the ground) except with the permission of the airspace owner.
G	No	Everywhere else. VFR flight is unrestricted.

Figure 14.3: Airspace Classification

(602.05) Compliance with Instructions

This section requires passengers to comply with instructions given by the crew and the crew to comply with instructions from the Pilot-in-Command.

(602.06) Smoking

Smoking by passengers or crew is not permitted during takeoff or landing or at any time in an aircraft lavatory. Tampering with smoke detectors in a lavatory is also forbidden.

(602.07) Aircraft Operating Limitations

You may not fly an aircraft outside its operating limitations described in the flight manual or other prescribed document or placard.

(602.08) Portable Electronic Devices

As pilot you may not use, or allow a passenger to use, an electronic device that could interfere with the aircraft's systems.

(602.09) Fuelling with Engines Running

You may not fuel an aircraft with passengers on board while the engines are running unless there is an approved company procedure permitting it.

(602.10) Starting & Ground Running of Aircraft Engines

This section is designed to prevent aircraft engines being started or left running in a dangerous manner. Before starting an engine, the pilot's seat must be occupied by someone who can control the aircraft, or the aircraft must be prevented from moving. A seaplane must be located where it will not endanger people or property if it moves.

Similarly an engine may not be left running unless a pilot's seat is occupied or the aircraft is prevented from moving.

(602.11) Aircraft Icing

This section defines a *critical surface* on an aircraft as being the wings, control surfaces, rotors, propellers, all stabilisers and, if the aircraft has rear-mounted engines, the upper surface of its fuselage.

Having provided this definition, the section then requires that an aircraft be inspected by the pilot-in-command or his or her delegate when there is a likelihood of frost, ice or snow on a critical surface and forbids takeoff when this contamination is present.

For more information see the "clean aircraft concept" in section 11.8.3 on page 252.

(602.12/13) Takeoffs, Approaches & Landings over Built-Up Areas

You are not allowed to take off or land over a built-up area or open-air assembly of people (within 2,000 ft horizontally) except at an airport.

Exam Hint 32 *Note that this regulation explicitly uses the term* airport *rather than the more general term* aerodrome. *The implication is that you may not land at an aerodrome without a certificate, if doing so would require you to fly over an assembly of people.*

(602.14) Minimum Altitudes & Distances

Except when taking off or landing, you are not allowed to fly over a built-up area or an open-air assembly of people at an altitude at which you could not glide clear in the event of an emergency without creating a hazard to people on the ground. In any event you may not fly lower than 1,000 ft above the highest obstacle within 2,000 ft of the aircraft.

When not flying over a built-up area or open-air assembly of people, you may not fly within 500 ft of any person, vessel, vehicle or structure.

Exam Hint 33 *This regulation confuses some students. It does* not *say that you are forbidden to fly lower than 500 ft AGL. If there are no people, vessels, vehicles and structures around, then the law permits you to fly at 1 foot above the ground except in control zones. This may not be safe or sensible, but it is legal. In control zones, section 602.114 prohibits flight below 500 ft AGL.*

(602.15) Permissible Low Altitude Flight

In spite of the restrictions in paragraph 602.14 (above), you may fly at altitudes and distances less than those specified, as long as you do not create a hazard to people or property on the ground for a number of operations including police work, saving human life, fire-fighting or air ambulance operations, the administration of the Fisheries Act or the Coastal Fisheries Protection Act, the administration of a national or provincial parks or for flight training conducted by or under the supervision of a qualified flight instructor.

(602.19) Right of Way—General

In general you are required to take whatever action is required in order to avoid collision. In particular you must give way to any aircraft that has declared an emergency.

Beyond these extreme conditions, the rules are reasonably sensible: more manoeuvrable aircraft give way to less manoeuvrable ones:

- power-driven aircraft give way to airships, gliders and balloons
- airships give way to gliders and balloons
- gliders give way to balloons
- power-driven aircraft give way to aircraft that are towing gliders or other objects or carrying a slung load.

When two equally manoeuvrable aircraft are converging, the pilot with the other aircraft on his or her right must give way. If two aircraft are approaching approximately head-on, then both aircraft must turn to the right.

Anecdote 57 *In addition to turning right, the quickest way of avoiding a collision might be to descend. I was once on a collision course with an aircraft that my passenger could see, but which I could not. My passenger was seriously concerned and, as I couldn't spot the other aircraft, it was difficult to know which way to turn for safety. I put the aircraft into a severe slip and lost altitude rapidly, avoiding the danger. The problem with using descent in this way is, of course, that the other pilot might also descend.*

If you are in flight or manoeuvring on the ground you must give way to an aircraft that is landing or about to land and, if you are yourself landing, you must give way to aircraft at lower altitude.

An aircraft that is being overtaken has the right of way over any overtaking aircraft; the overtaking aircraft must deviate and overtake on the right.

(602.20) Right of Way—Manoeuvring on Water

The rules when on water are basically the same as those on land or in the air: an aircraft must give way to an aircraft or vessel on its right and if two aircraft are approaching each other approximately head-on then they must turn right.

(602.21) Avoidance of Collision

You may not operate an aircraft so close to another aircraft as to create a risk of collision.

(602.22) Towing

You may not tow anything with an aircraft unless the aircraft is fitted with a tow hook and release control mechanism.

(602.23) Dropping of Objects

You may not drop anything from an aircraft in flight that will create a hazard to people or property on the ground.

Note that, subject to this condition, dropping things *is* allowed. This permits the "flour bombing" competitions that many flight schools organise and the fairly common practice of dropping human ashes from an aircraft.

(602.24) Formation Flight

You may not fly in formation with other aircraft unless all of the pilots-in-command have prearranged it and, if you are in a control zone, unless it has also been agreed by ATC.

(602.25) Entering or Leaving an Aircraft in Flight

No one is allowed to enter or leave an aircraft in flight without the permission of the pilot-in-command. The pilot-in-command may only give that permission for parachute jumps or when a special flight operations certificate has been issued (typically for air shows).

(602.26) Parachute Descents

Unless you have a special flight operations certificate, you may not allow anyone to parachute from an aircraft in or into controlled airspace or an air route or over or into a built-up area or an open-air assembly of people.

(602.27) Aerobatic Manoeuvres

You may not fly aerobatics:

- over a built-up area or an open-air assembly of people
- in controlled airspace or below 2,000 ft AGL unless you have a special flight operations certificate
- when flight visibility is less than three miles

(602.28) Aerobatic Manoeuvres with Passengers

If you have a passenger on board, you may not perform aerobatics unless you have either had at least 10 hours dual flight instruction in aerobatics or 20 hours aerobatic experience and have flown at least one hour of aerobatics in the preceding six months.

(602.30) Fuel Dumping

Pilots generally dump fuel to lighten the aircraft in emergency situations, particularly where there is a need to return to land shortly after takeoff and the aircraft is over gross landing weight.

This section of the CARs prohibits you from dumping fuel during flight unless it is essential to ensure safety. Even then you must take all possible measures to prevent danger to humans and damage to the environment.

(602.31) Compliance with ATC Instructions & Clearances

You must acknowledge and comply with all instructions from ATC that you receive in controlled airspace.[4] If you are flying IFR you must read back and comply with clearances. When flying VFR, unless specifically requested by ATC, the only type of clearance that needs to be read back is a hold-short clearance during taxiing.

You may deviate from a clearance or instruction if necessary to avoid a collision but, if you do, you must inform ATC as soon as possible.

Anecdote 58 *I have heard from many controllers that VFR pilots using transmission time reading back assigned headings or altitudes is one of their major causes of stress. Typically a simple call sign and* Wilco *suffices:*

ATC: Papa Tango November, turn left to 120 and start your descent now.

PTN: Papa Tango November, Wilco.

The underused term Wilco *means "I have received and understood your transmission and will comply with the instruction".*

(602.32) Airspeed Limitations

Below 10,000 ft ASL the maximum allowed airspeed is 250 knots. Below 3,000 ft AGL within 10 nautical miles of a controlled airport this reduces to 200 knots unless ATC clears you to fly faster.

(602.34) Cruising Altitudes & Cruising Flight Levels

The hemispherical rule for flight altitudes is based on track (rather than heading): true track in the Northern Domestic Airspace and magnetic track elsewhere. The rule applies to all IFR flights and all VFR flights above

[4] Or in uncontrolled airspace if an ESCAT plan has been activated—see section 14.6.10.

3,000 ft AGL. Below 18,000 ft, the appropriate altitudes are listed in figure 14.4.

Track 000° to 179°		Track 180° to 359°	
IFR	VFR	IFR	VFR
1000		2000	
3000	3500	4000	4500
5000	5500	6000	6500
7000	7500	8000	8500
9000	9500	10,000	10,500
11,000	11,500	12,000	12,500
13,000	13,500	14,000	14,500
15,000	15,500	16,000	16,500
17,000	17,500		

Figure 14.4: Appropriate Cruising Altitudes

(602.35) Altimeter-setting in the Altimeter-setting Region

When you are flying in the altimeter-setting region (effectively all but the far north of Canada),[5] you must adjust all altimeters to the pressure of the departure airport (or, if no pressure setting is available, the altitude of the airport) before takeoff. While flying you must reset the altimeters to the setting of the nearest station along the route of flight and before starting a descent for landing, you must adjust the altimeters to the pressure of the destination airport, if that information is available.

(602.36) Altimeter-setting in the Standard Pressure Region

When you are flying in the standard pressure region (the far north of Canada), you must adjust all altimeters to the pressure of the departure airport (or, if no pressure setting is available, the altitude of the airport) before takeoff. After takeoff and before reaching cruise altitude you must set the altimeters to 29.92″ Hg. Immediately before starting a descent for landing you must set the altimeters to the setting of the destination, if that is available.

(602.37) Altimeter-setting & Operating Procedures in Transition between Regions

The two sections above deal with flying in the altimeter setting or standard pressure regions; this section deals with flying between them. When you fly into the standard pressure region, set your altimeters to 29.92″ Hg immediately after entry; when flying into the altimeter-setting region reset your altimeters immediately before entry to the setting of the nearest station.

[5]The boundary of the altimeter setting region (the Southern Domestic Airspace) is clearly shown on the LO5 chart and it often surprises people to learn that places like Inuvik, Yellowknife, Churchill and Iqaluit are in the Southern Domestic Airspace.

(602.40) Landing at or Takeoff from an Aerodrome at Night

Unless you are part of a police operation or are saving human life, you may neither land at nor take off from an unlit airport at night: see chapter 14.4 for requirements on lighting.

14.6.4 (602) Operational & Emergency Equipment

This section deals with the emergency equipment that must be on board a Canadian aircraft or foreign aircraft being flown by a Canadian. This includes:

- current navigation charts or databases (in the case of GPS) for the route of the flight and, if the aircraft is flying VFR Over-The-Top, night VFR or IFR, any diversionary route.
- a hand-held fire extinguisher, timepiece and flashlight readily available to each flight crew member.
- a first aid kit.
- checklists for normal (pre-start, pre-takeoff, post-takeoff, pre-landing check) and emergency procedures.
- survival equipment for each person on board, given the geographical area and season of the year, that provides a way of starting a fire, providing shelter, purifying water and visually signalling distress (there are certain exemptions to this, e.g., for multi-engined aircraft flying IFR in controlled airspace south of 66°30′ north).

The rules for flight over water are also included in this section of the CARs:

- If you take off or land on water or fly beyond a point where the aircraft could reach shore in the event of an engine failure, you must carry a life preserver, individual flotation device or personal flotation device for each person on board.
- If you fly more than 50 nautical miles from shore then you must carry a life preserver for each person on board.

- Every life preserver, individual flotation device and personal flotation device must be easily accessible to the person for whose use it is provided when that person is seated.
- If you fly either a multi-engined aeroplane that cannot cruise with any engine failed or a single-engined aeroplane over water more than 100 nautical miles or 30 minutes of cruise from a suitable emergency landing site, you must have sufficient life rafts on board to carry all the crew and passengers.
- If you fly a multi-engined aeroplane over water at more than 200 nautical miles, or 60 minutes in cruise, from a suitable emergency landing site you must carry sufficient life rafts for the passengers and crew. For a transport category aircraft, the figures are raised to 400 nautical miles and 120 minutes.

All life rafts must be easily accessible and be equipped with a survival kit suitable for providing shelter, providing or purifying water and visually signalling distress.

Anecdote 59 *One of the most useful aviation training courses that I ever took was a so-called "dunking" course. Following some hours of ground school we were taken to a swimming pool where a realistic aircraft cockpit had been set up on a ramp. It had been stressed to us in the ground school that, when the aircraft hits the water and topples over, the pilot's first reaction is to undo the seat belt, "I am trapped by the seat belt in a sinking aircraft, I must undo it". This is wrong because the pilot will often then float upside down and lose orientation. A very common problem is the pilot then breaking the door handle off by forcing it the wrong way, trapping himself or herself in the cockpit. The cockpit used for the dunking course had a door handle that was designed to break off immediately if moved the wrong way. The first time the cockpit was launched down the ramp and I felt the whole structure toppling over as it sank, the instinct to release the seat belt too soon was almost irresistible. I would recommend this type of training to all pilots.*

14.6.5 (602) Flight Preparation, Plans & Itineraries

The first part of this section is a "catch-all" that says that, as a pilot-in-command, before taking off you must be familiar with the available information (including weather information) appropriate to the flight. Precisely what is meant by "available information" is not defined but presumably it includes weather reports, forecasts, NOTAMs and PIREPs.

The remainder of this section of the CARs deals with flight plans and flight itineraries. The required content of a Flight Plan or Flight Itinerary is given on the back cover of the Canada Flight Supplement.

If you are flying VFR more than 25 miles from the departure aerodrome then you must file either a flight plan or flight itinerary. If you are flying internationally, then an itinerary is not adequate and a flight *plan* must be filed. Generally a flight plan is filed with ATC, an FSS or a community aerodrome radio station, whereas an itinerary is filed with a "responsible person". If, however, the flight is to penetrate the Air Defence Identification Zone (see section 14.6.10), the flight itinerary must be filed with ATC, an FSS or community aerodrome radio station.

Anecdote 60 *Soon after I got my pilot licence I went flying with a friend and left a flight itinerary with my wife—instructing her that if I didn't contact her by a particular time she was to contact Flight Services and report an aircraft overdue. We were delayed and I realised that we wouldn't be back in time. Unfortunately this was before the days of ubiquitous cellular telephones and I had no way of contacting my wife. I radioed Flight Services and told them that if an agitated woman called to report us overdue, then they were to reassure her that we were OK. This happened, and the talking-to I got on landing convinced me never to use close family members as responsible people again!*

Exam Hint 34 *Many students misremember the 25 nautical miles rule. Faced with the question "On what flight must you file a flight plan?" they respond with the 25 mile rule. Actually the only time a flight* plan *is required is for international flights—otherwise a flight* itinerary *can always be used.*

If you are flying IFR, then you must always file a flight plan or flight itinerary irrespective of the distance you will be flying. You may use an itinerary if any of the flight is outside controlled airspace.

Anecdote 61 *I often fly cross-country trips with several other aircraft and generally we don't file flight plans—we use each other as "responsible persons" and use itineraries. Flying back from the USA once with five or six other aircraft, I was approaching Canadian*

airspace (heading over Lake Ontario towards Kingston) when it suddenly occurred to me that I hadn't filed a flight plan. I was within radio range of Kingston FSS and just before entering Canada I had to air-file a flight plan from "current location" to Kingston while flying 360° patterns.

If you file a flight plan or flight itinerary with ATC, an FSS or a community radio station, then you must close it as soon as possible after arrival. Closing a flight plan must be done before the search and rescue time specified in the flight plan or, if no time was specified, within one hour of the estimated time of arrival.

14.6.6 (602) Pre-Flight & Fuel Requirements

Pre-Flight

You must ensure before takeoff that all baggage, equipment and cargo are either stowed in a bin, compartment or rack certified for storage or restrained to prevent them from shifting. This storage must not obstruct the normal and emergency exits or the aisles between the flight deck and the passenger compartment and must not prevent a crew member from reaching all parts of the aircraft with a fire extinguisher.

Additionally, if the aircraft can carry ten or more passengers, and passengers are actually being carried, storage of baggage and equipment must not obstruct a passenger's view of a "seat belt", "no smoking" or exit sign. For this size of aircraft, it is also necessary that all passenger service carts and trolleys be securely restrained during movement on the ground, during takeoff and landing and during in-flight turbulence. All video monitors suspended from the ceiling must also be stowed and securely restrained during takeoff and landing.

Before takeoff the pilot-in-command has the responsibility of ensuring that all crew members have been instructed on the duties they are to perform and the location and use of all of the normal and emergency exits and of all of the emergency equipment carried on board the aircraft.

Fuel Requirements

This section defines the fuel that must be on board an aircraft at the start of a flight. In calculating the fuel required, you must take into account taxiing and foreseeable delays prior to takeoff, meteorological conditions, foreseeable air traffic routings and traffic delays, the need to land at a suitable aerodrome if cabin pressurisation or any engine fails at the most critical point during the flight and any other foreseeable conditions that could delay the landing of the aircraft.

Given this context, the fuel requirements for a day VFR flight are enough fuel to fly to the destination and then fly for another 30 minutes at normal cruising speed. For a night VFR flight the 30 minutes is increased to 45.

Anecdote 62 *Remember that, for reciprocating engines without automatic leaning, fuel burn values in the operating handbook are accurate only if the engine is properly leaned. On my pre-flight-test for my instrument rating (the mock test before the real flight test), my instructor and I flew in cloud for the whole of the test. We made some approaches at an uncontrolled airport without breaking out of cloud and then returned to the nearby international airport to fly the ILS. The cloud base had been forecast to stay at about 800 ft AGL all day so we felt that the ILS should be easy and then we would get special VFR clearance out of the zone to return to our home airport. As we approached the international airport we were told that a Dash-8 ahead of us had reported the ceiling at 250 ft. Suddenly the need to reach an alternate airport was real: if the ceiling dropped another 50 ft we wouldn't be able to land at the international. I then noticed that, under the pressure of the flight test, I had flown the entire flight test with the mixture fully rich. Without any POH figures for the fuel burn when fully rich, we suddenly had no idea whether or not we could reach our alternate—an hour's flying distance away. As it happened we broke out at 250 ft and landed at the international airport, but my failure to lean the mixture gave both my instructor and me a real fright.*

Passenger Briefings

You must brief your passengers before flight, and the briefing must include:

- the location and operation of emergency and normal exits
- the location and operation of safety belts, shoulder harnesses and restraint devices
- the positioning of seats and the securing of seat backs and chair tables
- the stowage of carry-on baggage
- if the aircraft is unpressurised and it is possible that the flight will require the use of oxygen by the passengers, or where the aircraft is pressurised and operated above FL 250, the location and operation of oxygen equipment

- any prohibition against smoking
- for flight over-water, the location and use of life preservers, individual flotation devices or personal flotation devices
- the location and use of first aid kits and survival equipment
- for a small aircraft, the location and means of operation of the ELT.

Anecdote 63 *When briefing the examiner during a flight test, don't forget that, on some aircraft, baggage compartment doors can be opened from the inside. On one of my flight tests I briefed the examiner (acting as passenger) on the two doors of the Cessna 172 we were flying. During the debriefing afterwards she told me that I had lost a point because there were actually three doors on the 172—I had not mentioned the baggage compartment door.*

14.6.7 (602) Operation at or in the Vicinity of an Aerodrome

General

This section of the CARs starts by defining the pilot-in-command's responsibilities for ensuring that, before takeoff or landing, there is no likelihood of collision with another aircraft or a vehicle and that the aerodrome is suitable for the intended operation.

It then defines your responsibilities at or close to an airport; as pilot-in-command you must:

- look for traffic
- conform to (or avoid if you are not landing) the circuit pattern
- make all turns to the left while in the circuit unless right turns are specified in the CFS or authorised by ATC
- where practicable, land and takeoff into the wind
- listen on the appropriate radio frequency
- obtain the necessary clearances to taxi, take off or land at controlled aerodromes
- remain at least 2,000 ft above an aerodrome unless you are taking off or landing or performing one of a number of approved activities (e.g., taking part in a police or fire-fighting operation or saving human life)
- ensure, if you are flying passengers in an aircraft capable of carrying 20 or more passengers to or from an airport (i.e., a certified aerodrome), that the airport has an aircraft fire-fighting service.

Mandatory Frequency Zones

Some uncontrolled airports have a mandatory frequency (MF) zone around them. You may not fly either VFR or IFR into such a zone unless either:

1. the aircraft is equipped with a radio, or
2. you have previously notified the ground station of your intentions and, when you arrive, you fly a complete circuit (normally a complete circuit is not required at an aerodrome in an MF zone).

At all times while you are in the zone you must listen on the zone frequency and make announcements to the ground station (or "traffic" if there is no ground station):

- before taxiing onto the manoeuvring area
- before moving onto the runway
- after takeoff when leaving the circuit
- when clear of the MF zone
- five minutes and immediately before entering the MF zone
- when joining the circuit
- when on the downwind leg
- when on final approach
- when clear of the manoeuvring area after landing

Noise

When flying at any aerodrome, the pilot-in-command is responsible for complying with any noise abatement procedures and noise control requirements specified in the CAP or CFS. These may include preferential runways, minimum-noise routes, hours when operations are prohibited or restricted, the prohibition or restriction of training flights and the minimum allowed altitude in the vicinity of the aerodrome.

The remainder of this section of the CARs covers the noise certification requirements on aircraft of over 34,000 kg (74,956 pounds) at a number of international airports.

14.6.8 (602) Visual Flight Rules

VFR Flight Conditions

In order to fly VFR you must fly with visual reference to the ground. The precise meaning of this has been queried by the Transportation Safety Board as a result of a number of accidents that have occurred when an aircraft has taken off on a very dark night in an area where there is little artificial light: in those conditions can flight be said to be taking place "with visual reference to the ground" even if the aircraft is not in cloud? TSB Recommendation A16-08 states *"... the Board recommends that the Department of Transport amend the regulations to clearly define the visual references (including lighting considerations and/or alternate means) required to reduce the risks associated with night visual flight rules flight."* In some countries, night flight must always be conducted under IFR.

The rule as it stands, means that a pilot may fly above an incomplete layer of cloud as long as there are sufficient gaps to allow visual reference to the ground.

Other conditions required for VFR flight differ, depending on whether the flight is in controlled or uncontrolled airspace (see figure 14.3 for a description of controlled and uncontrolled airspace). Figure 14.5 specifies the minimum legal conditions for VFR flight. These visibility minima may be overridden for some commercial aerial work—see section 14.7.3.

There is one additional constraint specified in this section: when you are in a control zone you must fly at least 500 ft AGL, except for taking off or landing.

VFR Over-The-Top

As described above, generally VFR flights must be made "with visual reference to the ground". VFR Over-The-Top (OTT) allows pilots with an instrument rating, commercial licence or VFR OTT rating to fly without visual reference to the ground as long as the weather forecast for the destination aerodrome meets certain conditions:

- sky clear or scattered cloud
- visibility of at least five miles
- no precipitation, fog, thunderstorms or blowing snow forecast

from one hour before to two hours after the predicted arrival time (if the aerodrome has a TAF) or until three hours after (if the aerodrome does not have a TAF).

Once in the air flying VFR OTT you must maintain a visibility of at least 5 miles, stay at least 1,000 ft vertically from cloud and, if you fly between cloud layers, the layers must be at least 5,000 ft apart.

Anecdote 64 *I have only once found conditions to be amenable to flying VFR OTT: a short flight from Ottawa Rockcliffe to Watertown, New York. The clouds were broken around Ottawa with a number of reasonable holes and, towards the St Lawrence river, the clouds were reported to have disappeared. Since cloud bases around Ottawa were about 2,000 ft I decided it would be more convenient to fly up through a hole and fly over the top. Frankly I was willing to do this only because I knew that, if clouds were covering Watertown, I could file an IFR flight plan from the air and fly an IFR approach.*

Exam Hint 35 *Note that no requirements are placed on the weather at the departure aerodrome: if you can find a hole in the clouds that allows you to maintain the cloud clearances then you may launch on a VFR OTT flight based on only the forecast at the destination.*

It is unclear how, before deciding to fly VFR OTT, you can determine that the cloud layers you will meet *en route* will be at least 5,000 ft apart or that the flight visibility will be at least 5 miles—this type of information is not contained in any standard Canadian forecast. However, it *can* be deduced from the Skew-T forecasts; see section 5.4.4 on page 104. It would be unfortunate to launch VFR OTT and find *en route* while flying above an undercast that the visibility was reducing, leaving you with no options.

Exercise 105 *You are intending to fly from airport A to airport B at 8,000 ft ASL and would like to fly VFR OTT. The latest METAR from airport A indicates broken cloud at 3,500 ft AGL (4,500 ft ASL) in light snow. The TAF for airport B indicates FEW clouds at 2,500 ft AGL (3,000 ft ASL) with visibility of five miles for the period of 3 hours before until 2 hours after your estimated arrival time. May you fly this flight VFR OTT?*

Special VFR

As shown in figure 14.5, generally the visibility within a control zone has to be at least 3 miles for a VFR aircraft to enter. If, however, the aircraft has a radio and visibility is at least 1 mile, a pilot may request[6] a

[6]Note that the pilot must request this: it is never suggested by ATC although they are known to drop hints: "Visibility is now two miles. Is there anything *special* you would like?"

	Uncontrolled Airspace		Controlled Airspace
	Below 1000 ft AGL	1,000 ft AGL or above	
Visibility by day at least...	2 miles	1 mile	3 miles
Visibility at night at least...	3 miles	3 miles	3 miles
Vertical distance from cloud at least...	clear	500 feet	500 feet
Horizontal distance from cloud at least...	clear	2000 feet	1 mile

Figure 14.5: Conditions for VFR Flight

"special VFR" clearance from ATC. While flying on this clearance the pilot is required to remain clear of cloud and maintain visual reference to the ground.

14.6.9 (602) Radiocommunications

When you are flying VFR in Class B, C or D airspace and you find that the two-way communication with ATC has failed, you must

- leave the airspace. If you are in a control zone you should land at the aerodrome in the zone, otherwise leave by the shortest route.
- squawk 7600 if you have a transponder.
- inform ATC as soon as possible of the action you have taken.

14.6.10 (602) Emergency Communications & Security

This section of the CARs covers a number of topics including interception and flying into and within the Air Defence Identification Zone (ADIZ). It also requires that any two-way VHF radio that you use in an aircraft be capable of operation on 121.5 MHz, the international emergency frequency.

Interception

The Canada Flight Supplement contains a list of the signals that are used when one aircraft intercepts another. Only peace officers, officers of the Canadian Forces acting within their duties and people otherwise authorised by the Minister are allowed to issue an interception order.[7]

If you are intercepted and told to land then you must do so unless you get counter-instructions from ATC.

[7]Note that the term "peace officer" is defined in the Canadian Criminal Code to include a pilot-in-command of an aircraft.

ADIZ

The ADIZ is an area of airspace around the three borders of Canada through which it has never been invaded: the western, northern and eastern. The extent of the ADIZ is defined in the *Designated Airspace Handbook* and is shown on aviation charts.

In summary, the rules regarding flying in the ADIZ are as follows:

1. A flight plan or flight itinerary must be filed with an FSS, ATC unit or a community aerodrome radio station for every flight that will enter the ADIZ. Leaving an itinerary with a responsible person (see section 14.6.5) is not sufficient.
2. If you are flying VFR starting outside the ADIZ, the flight plan or itinerary must include the estimated time and place of entering the ADIZ. As soon as possible after takeoff, the pilot should file a position report with ATC or an FSS including the point of departure and the estimated time of entry into the ADIZ.
3. If a VFR flight starts inside the ADIZ, then a position report should be filed with ATC or an FSS as soon as possible after takeoff.
4. During VFR flight, if the estimated time of entering the ADIZ changes by more than 5 minutes, or the point of entry changes by more than 20 nautical miles then the pilot must revise this information with ATC or an FSS.

ESCAT

The Emergency Security Control of Air Traffic (ESCAT) plan would be invoked if there were a threat to Canadian national security requiring non-essential aircraft to be ordered from particular airspace. ESCAT has replaced the Security Control of Air Traffic and Air Navigation Aids (SCATANA) process.

If a pilot is notified by ATC that the ESCAT Plan has been implemented, then explicit approval from ATC

or an FSS is required before takeoff, and once in the air the pilot must comply with instructions from ATC (even in uncontrolled airspace where ATC cannot normally issue instructions) and provide position reports at least every 30 minutes while in uncontrolled airspace.

14.6.11 (603) Special Flight Operations

Special Flight Operations include air shows, low level air races, aerobatic competitions, fly-ins, balloon festivals and parachuting. These may only be held if the organiser has a special flight operations certificate.

14.6.12 (604) Private Operator Passenger Transportation

This section of the CARs deals with the private operation (e.g., as a corporate jet) of a turbine-powered, pressurised or large aircraft (i.e., one with a certified takeoff weight greater than 5,700 kg (12,566 pounds)) carrying passengers. In this case, the operator must hold a private operator certificate for the aircraft issued by the Canadian Business Aviation Association.

14.6.13 (605) Aircraft Requirements

This section lays out the documents that must be on board an aircraft during flight. The contents of these documents are covered in more detail in section 11.1.5 on page 231 but include:

- a flight authority—the Certificate of Airworthiness or Flight Permit
- the aircraft's flight or operating manual
- all necessary markings or placards in the cockpit

In addition to these items, you may not fly an aircraft with inoperable equipment if that equipment is required by the minimum equipment list, or if you consider the aircraft to be unsafe.

14.6.14 (605) Aircraft Equipment Requirements

Minimum VFR Equipment

Figure 14.6 lists the instruments that need to be on board an aircraft for a Day VFR, Night VFR or VFR OTT flight.

Lighting

Unless you decide it is in the interests of safety to turn them off, you may not operate an aircraft in the air or on the ground at night, or on water between sunset and sunrise, unless its position lights and anti-collision lights are turned on.

Seat Belts

Seat belts must be worn during taxiing, takeoff and landing and at any time that the pilot-in-command considers them necessary.

You may not fly an aircraft unless it has a seat and safety belt with a metal-to-metal clasp for each person on board other than an infant, a parachutist or a patient on a stretcher. Parachutists and patients must have some form of restraint system.

The rules for when a seat must also be equipped with a shoulder harness are quite complex. In summary, a shoulder harness is required for:

- each front seat in a small aircraft manufactured after 18th July, 1978
- each flight attendant's seat in a transport category aircraft
- each forward- or aft-facing passenger seat in small aircraft designed for fewer than 10 passengers, manufactured after December 12, 1986
- each seat in an aircraft used for aerobatics or aerial inspection below 500 ft AGL

If you are using a restraint system instead of a seat belt for a child, then the child must be within the weight and height limits specified by the restraint system's manufacturer and the child must be accompanied by a parent or guardian seated in an adjacent seat. The restraint system must bear a legible label indicating the applicable design standards and date of manufacture, and must be secured by the safety belt of a forward-facing seat not in an emergency exit row.

Flight Control Locks

You may not use a flight control lock unless it is incapable of becoming engaged when the aircraft is being operated and a warning is provided to the pilot whenever it is engaged.

De-icing or Anti-icing Equipment

You may not take off or continue a flight in an aircraft where icing conditions are forecast or reported unless the aircraft is equipped to operate in icing conditions in accordance with its type certificate.

Item	Day VFR	Night VFR	VFR OTT	Notes
Altimeter	Y	Y	Y	Must be a sensitive altimeter in controlled airspace
Airspeed Indicator	Y	Y	Y	
Magnetic Compass	Y	Y	Y	Must be independent of electrical system
Tachometer	Y	Y	Y	For each engine and propeller
Oil Pressure Indicator	Y	Y	Y	For each engine with oil supply
Coolant Temp. Indicator	Y	Y	Y	For each liquid-cooled engine
Oil Temp. Indicator	Y	Y	Y	For each air-cooled engine
Manifold Pressure Gauge	Y	Y	Y	For each appropriate engine
Fuel Level Indicator	Y	Y	Y	Must be visible from the control position
Landing Gear Indicator	Y	Y	Y	For aircraft with retractable landing gear. Must be visible from the control position
Appropriate Radios	Y	Y	Y	For operation in class B, C, D airspace, MF zones and the ADIZ
Turn Co-ordinator	N	Y	Y	Or turn and slip indicator
Spare Fuses	N	Y	N	At least 50% of the number of each type of fuse used (at least one)
Heading Indicator	N	Y	N	For operation in Northern Domestic Airspace at least one HI not dependent on the earth's magnetic field
Lighting	N	Y	N	For all instruments
Landing Light	N	Y	N	If carrying passengers
Anti-Collision Lights	N	Y	N	
Pitot Heater	N	N	Y	
Radio Navig. Equipment	N	N	Y	

Figure 14.6: Minimum Equipment for VFR Flight

Oxygen Systems

The requirements for carrying oxygen systems on board an aircraft are summarised in figure 14.7. In addition to the requirements to carry oxygen, there are also requirements on its use:

- At cabin-pressure-altitudes between 10,000 and 13,000 ft ASL for more than 30 minutes, each crew member must use supplemental oxygen for the whole flight.
- At cabin-pressure-altitudes above 13,000 ft ASL, each person on board the aircraft must use supplemental oxygen for whole flight.
- The pilot flying an aircraft must use supplemental oxygen if the aircraft does not have quick-donning oxygen masks[8] and is operated at or above FL250 or, even if it *is* equipped with quick-donning oxygen masks, when it is operated above FL410.

Transponders

Without previously-obtained permission from ATC, you may not fly an aircraft in transponder airspace without a transponder and automatic pressure-altitude reporting equipment—see section 10.1.5 on page 208.

[8] i.e., an oxygen mask that provides an immediate supply of oxygen and that can be fitted using one hand within five seconds.

Emergency Locator Transmitters

Descriptions of the different types of ELT are given in section 11.9.3 on page 255. All aircraft operating over land must be fitted with a type AD, AF, AP, A or F ELT. Large multi-engined turbojet aircraft engaged in an air transport service carrying passengers over water need two ELTs of type W or S.

The major exemptions to carrying an ELT are:

- Flight training or parachute jump aircraft flying within 25 nm of the home base.
- Ultralights.
- Aircraft where the ELT has been removed for certification. In this case a placard must be mounted in the cockpit saying that the ELT is not fitted and giving the date when it was removed. In this circumstance, the aircraft may be without an ELT for 10 days if it is being used in commuter or airline operations, otherwise for 30 days.

Aircraft Type	Who?	When?
Any	All crew and 10% of passengers (minimum 1)	Flights over 30 mins between 10,000 ft and 13,000 ft ASL
Unpressurised or pressurised during an emergency descent	Everyone on aircraft	Flights over 13,000 ft ASL

Figure 14.7: Oxygen Requirements

Exam Hint 36 *There is a general belief in the pilot community that an ELT is not required in an aircraft flown within 25 nm of the home aerodrome. This is not true: the 25 nm exemption only relates to aircraft engaged in flight training or parachute jumps.*

An ELT may be activated for test purposes for up to 5 seconds during the first 5 minutes of any UTC hour, but otherwise you may not switch one on except in an emergency. If you inadvertently activate an ELT (for example, by a heavy landing) then you must inform ATC, an FSS or community aerodrome radio station as soon as possible.

14.6.15 (605) Maintenance

This section of the CARs deals with the maintenance that an aircraft must undergo. Unless you are flying an amateur-built or owner-maintained aircraft, you may only take off or allow anyone else to take off[9] in an aircraft that has been maintained in accordance with any airworthiness limitations, where all maintenance has been signed off by an Aircraft Maintenance Engineer (AME) and the aircraft meets all airworthiness directives.

The major exception to the requirement for an AME's sign-off is so-called "elementary" work. This work can be performed by any pilot and is defined to be the following.[10] Items 1 to 9 refer to small, privately-owned aircraft, the other items to all aircraft:

1. Installing small fabric patches
2. Changing tires, skis, wheels, landing skids or skid shoes when hydraulic lines are not affected
3. Repairing non-structural fairings, cover plates and cowlings
4. Cleaning and replacing spark plugs
5. Checking cylinder compression
6. Cleaning or changing of fuel, oil and air filters
7. Draining and replenishing engine oil
8. Checking the electrolyte level and specific gravity of lead acid batteries
9. Adjusting generator or alternator drive belt tension
10. Repairing upholstery, trim and cabin furnishings
11. Removing and replacing passenger seat belts and harnesses, fuses, light bulbs, reflectors, rack-mounted avionics, aircraft batteries, rapid-release co-pilot control levers, wheels, pedals, pedal guard plates induction system anti-icing baffles and scoops and deflectors
12. Opening and closing of non-structural access panels
13. Removing and replacing cabin doors on unpressurised aircraft
14. Removing, replacing and repositioning of non-structural partitions in the passenger cabin
15. Inspecting and continuity checking of self-sealing chip detectors
16. Removing, cleaning, replacing and adjusting external components of chemical dispersal systems
17. Checking and adjusting air pressure in tires with operating pressures below 100 psi

Exercise 106 *A pilot who is not a mechanic would like to remove the passenger door on her Cessna 172 to allow a passenger a clearer view of the ground during a photography flight. Such removal is permitted in the aircraft's POH. Is she allowed to remove and replace the door, or must this be performed by a mechanic?*

The schedule of maintenance for an aircraft has to be approved by the Minister. An aircraft is subject to an

[9] This latter phrase is intentional—it places the responsibility on the owner of an aircraft to inform a pilot of its maintenance state.

[10] The list in the CARs is exhaustive: if the work is on the list then it is "elementary"; if it is not on the list then it is not "elementary".

inspection every 100 hours of airtime for commercially-operated aircraft and every 12 months for non-commercial aircraft. An additional inspection is required if the aircraft has been subjected to an "abnormal occurrence". If it does not require disassembly, this additional inspection may be performed by the pilot-in-command.

Anecdote 65 *Although a privately-registered aircraft only needs to be inspected annually, a prudent owner will also have more frequent inspections if the usage requires it. I used to be one of 12 owners on an aircraft that was flying 300 hours per year and we decided that a "100 hour" inspection, although not legally required, would be prudent.*

14.6.16 (605) Technical Records

An owner of an aircraft must keep a journey log and a separate technical record for the airframe, each installed engine and each variable-pitch propeller. A weight and balance report must also be kept. If the aircraft is sold then these technical logs must be passed to the new owner. The technical logs must not be carried in the aircraft (since they will provide useful information were the aircraft to crash).

Anecdote 66 *I don't know whether this story is apocryphal, but it's a good story and so possibly worth including. It concerns a commercial aircraft at one of the airports in the far north of Canada. On arrival it was necessary to do some maintenance work so the technical logs were flown up in another aircraft (which then departed). The work was finished and the logs updated and signed. The pilot was carrying the logs onto the aircraft for the return trip south when he was told that this was not allowed: the technical logs could not be carried on the aircraft. He asked how they could be returned to the aircraft's home base, and was told that they should be sent by Canada Post. So the pilot parcelled them up and put them into the mail. The mail bags were then loaded on the aircraft for transfer to the sorting office...*

Every entry in the logs must be accurate, legible and permanent and must include the name and signature or employee identifier of the person making the entry.

The contents required in a journey log are listed in figure 14.8. In addition to these items, the pilot-in-command of an aircraft engaged in a commercial air service and operating in international flight must also record the names of all of the crew members and their duty assignments, the places and times of departure and arrival, the flight time, the nature of the flight (private, aerial work, scheduled or non-scheduled) and any incidents or observations relating to the flight. In general the only flights where you may fly without the Journey Log on board are those where you do not plan to land and shut down anywhere other than the point of departure.

If you hold technical records on a computer, rather than on paper, you must ensure that they are protected against inadvertent loss or destruction and against tampering and it must be possible to get printed copies if requested by the Minister.

When you fill one volume and switch to another, you must copy sufficient entries from the preceding volume to maintain an unbroken chronological record.

If you correct an entry in a technical record then you must strike out the incorrect entry in such a way that it remains legible, date the new entry and enter the reason for the correction. Even when the data are held on a computer it must be possible to read the old version of corrected entries.

14.6.17 (606) Munitions of War

This is perhaps one of the stranger sections of the CARs. It says that, without authorisation of the Minister, only Canadian aircraft are allowed to carry weapons, ammunition or other equipment designed for use in war in Canadian airspace.

14.6.18 (606) Synthetic Training Equipment

The term "synthetic training equipment" effectively means a simulator and this section of the CARs says that you may not use simulator for pilot training unless a flight simulator certificate is in force for the device. For the certificate to remain in force, the simulator must be checked at least every 6 months.

14.7 CARs Part VII

Part VII covers the operation of *commercial air services*. This term is defined in the Aeronautics Act to mean the use of an aircraft for hire or reward.

The CARs define four types of commercial air services:

1. Aerial Work: part 702 of the CARs—see section 14.7.3

2. Air Taxi: part 703 of the CARs—see section 14.7.4

Item	Time of Entry
Aircraft nationality, registration, manufacturer, type, model and serial number	When a new Journey Log is started
Aircraft empty weight and empty centre of gravity	When a new Journey Log is started and when the weight or centre of gravity changes
Air time of each flight or series of flights and cumulative total air time and landings since date of manufacture	Daily when at least one flight has been made
Particulars of any abnormal occurrence to which the aircraft has been subjected	As soon as possible after the occurrence but certainly before the next flight
Particulars relating to a conditional maintenance release	As soon as possible after the release is issued
The results of a test flight required after maintenance	As soon as possible after the test flight and certainly before the next flight
Particulars of any defect that becomes apparent during flight operations	As soon as possible and certainly before the next flight
Particulars of any maintenance or elementary work	As soon as possible after the maintenance and certainly before the next flight

Figure 14.8: Journey Log Entries

3. Commuter: part 704 of the CARs
4. Airline: part 705 of the CARs

The Commuter and Airline sections of the CARs are not required knowledge for the written examination and are therefore not included in this book.

The operator's *Company Operations Manual* is referred to several times in this section. The contents of such a manual can be found in section 723.105 of the CARs. Similarly, the contents of an *Aircraft Standard Operating Procedures Manual* can be found in section 723.107 of the CARs.

14.7.1 (700) General

You may not operate an air transport service unless you hold an air operator certificate. Without such a certificate you may not operate an aircraft that is carrying passengers, towing objects or dispersing products (e.g., crop spraying). There are some exceptions to these rules:

- a farmer who owns an aircraft may spray crops within 25 miles of the centre of his or her farm.[11]
- flight training units may use single-engined aircraft to carry passengers on sight-seeing flights if the pilot is a certified flight instructor.

[11] This rules does not seem to preclude farmers from spraying their neighbours' crops as long as they are within 25 miles.

14.7.2 (700) Flight Time & Flight Duty Time

An air operator must have a system to monitor the flight time, flight duty time and rest periods of each of its crew. The operator is not allowed to assign a crew member for flight time (nor may the crew member accept such an assignment) if the total time of all flights conducted by the flight crew member will, as a result, exceed

- 1,200 hours in any 365 consecutive days
- 300 hours in any 90 consecutive days
- 120 hours in any 30 consecutive days or, in the case of a flight crew member on call, 100 hours in any 30 consecutive days
- 60 hours in any 7 consecutive days
- 8 hours in any 24 consecutive hours if flying single-pilot IFR

The only occasion when these limitations may be exceeded is when the flight is extended for at most 3 hours as a result of unforeseen operational circumstances and the pilot-in-command considers it safe to exceed the times. The rest period following the flight must then be extended by at least the additional duty time.

Exam Hint 37 *Although in practice these flight crew hours would be looked up when needed rather than being memorised, they do form a convenient set of numbers for examination questions. You need to learn them for the written examination.*

14.7.3 (702) Aerial Work

Flight Operations

An air operator is responsible for ensuring that all personnel are properly instructed in their duties.

No one may start a flight unless the flight has been authorised in accordance with the procedures specified in the company's operations manual.

The VFR visibility rules specified in section 14.6.8 may be overridden for some commercial operations. In particular an aircraft in day VFR flight in uncontrolled airspace at less than 1,000 ft AGL may be operated when flight visibility is less than two miles if:

- this is authorised in an air operator certificate and
- the aircraft has an artificial horizon, a directional gyro or gyro compass and a GPS receiver and
- the pilot has at least 500 hours of experience and
- the pilot has received recurrent human factors and flight training

Unless it is specifically authorised to do so in its air operator certificate, an air operator may not:

- operate an aircraft at night, in VFR OTT or IFR flight while towing or dispersing products
- operate a single-engined aircraft at night, in VFR OTT or IFR flight
- operate an aircraft carrying passengers at night unless the pilot-in-command has an instrument rating
- operate a land aircraft over water beyond a point where it could reach shore in the event of an engine failure

Aircraft Equipment Requirements

This section of the CARs expands the equipment requirements described in section 14.6.14 of this book to cover commercial operations. In summary, at least one landing light is required for night operations, the pilot's seat and any seat beside it must have a safety belt with shoulder harness and no external loads may be carried unless the attachment device is authorised in a supplemental type certificate or in an airworthiness approval for the aircraft.

Personnel Requirements

For each flight, an air operator must designate a pilot-in-command and, for two-pilot crews, a second-in-command. The crew members must be suitably qualified and suitably trained. For all pilots except the chief pilot, this includes having successfully completed a pilot proficiency check within the last 2 years and the air operator's ground and flight training programme within the last year.

Training

An air operator must establish and maintain a ground and flight training programme approved by the Minister to ensure that each member of staff has the necessary skills to carry out his or her work. This training must include company "indoctrination", training in the aerial work to be conducted and initial and annual training on the aircraft type, aircraft servicing, ground handling and emergency procedures. Additionally, pilots and operations personnel must also have surface contamination training (i.e., training regarding ice or frost on flying surfaces).

Manuals

An air operator must make the appropriate parts of its company operations manual available to each crew member and to its ground operations and maintenance personnel. As the manual changes, the changes must be applied to all copies.

For each aircraft needing two or more pilots, an air operator must establish and maintain standard operating procedures. A copy of this must be carried on board the aircraft.

14.7.4 (703) Air Taxi Operations

Flight Operations

No one may start a flight unless the flight has been authorised and a flight plan prepared in accordance with the company's operations manual. The pilot-in-command must ensure that a copy of the flight plan is left at the point of departure and the air operator must retain a copy of the flight plan for the period specified in the company operations manual.

Unless authorised to do so in its air operator certificate, an air operator may not:

- operate a single-engined aircraft carrying passengers in IFR or night VFR flight

- operate a land aircraft over water beyond a point where it could reach shore in the event of an engine failure
- operate a single-engined aircraft with more than nine passengers on board
- operate an aircraft carrying an external load with passengers on board unless this has been authorised in a type certificate or supplemental type certificate

When passengers are on board, you may not simulate emergency situations that could affect the flight characteristics of the aircraft.

VFR Flight

Air Taxi operations are not allowed to be flown VFR unless current weather reports and forecasts indicate that the weather conditions along the route and at the destination aerodrome will be VFR—i.e., it is not permitted to take off and "see" whether VFR can be maintained for the whole flight. VFR Over-The-Top is forbidden unless explicitly permitted in the air operator certificate.

Except for takeoff and landing, it is not permitted to fly night VFR at less than 1,000 ft above the highest obstacle within three miles horizontally from the route to be flown. For day VFR the figures are 300 ft AGL or at a horizontal distance of less than 300 ft from any obstacle. During day VFR in uncontrolled airspace at less than 1,000 ft AGL, a pilot may fly when the flight visibility is less than two miles if this is authorised in an air operator certificate.

Routes in Uncontrolled Airspace

In uncontrolled airspace, IFR and night VFR flight may only be flown along air routes unless the operator establishes a different route in accordance with section 723.34 of the CARS: effectively defining minimum obstacle clearance altitudes, minimum *en route* altitudes and all of the other characteristics normally associated with an airway or air route. If these routes rely on private navigation aids then arrangements have to be made with the owners and, if they rely on public navigation aids, the company has to register to receive information about outages.

Weight & Balance

During every phase of the flight the load restrictions, weight and centre of gravity of the aircraft must conform to the restrictions in the flight manual. Note that, for air taxi operations, unless actual passenger weights are known, the segmented weight technique described in section 11.6.2 on page 248 must be used to determine weights.

Passenger Briefings

Details about what is to be included in the passenger briefings are contained in standard 723.39. These details are summarised here.

The pilot-in-command must ensure that passengers are given a safety briefing before takeoff. If the standard briefing is insufficient for a particular passenger because of his or her physical, sensory or comprehension limitations or because he or she is responsible for another person, the pilot-in-command must ensure that the passenger is given an individual safety briefing. In particular, passengers seated next to an emergency exit must be made aware of how to operate that exit.

If an emergency occurs in flight and time and circumstances permit, the pilot-in-command must again ensure that all passengers are given an emergency briefing.

Aircraft Equipment Requirements

As for aerial work operations—see section 14.7.3.

Personnel Requirements

For each flight, an air operator must designate a pilot-in-command and, for two pilot crews, a second-in-command.

The crew members must be suitably qualified and trained and must have completed at least three takeoffs and landing within the previous 90 days and successfully completed a pilot proficiency check and the air operator's ground and flight training programme within the last year.

In addition, anyone acting as pilot-in-command on a night VFR flight must be IFR-rated.

Training

As for aerial work operations—see section 14.7.3.

Manuals

As for aerial work operations—see section 14.7.3.

14.7.5 (706) Aircraft Maintenance Requirements

An air operator may not operate an aircraft unless it has been maintained in accordance with the air operator's Maintenance Control Manual. The person or organisation performing this maintenance must hold an Approved Maintenance Organisation (AMO) certificate

and have adequate facilities, equipment, spare parts and personnel available at the maintenance site.

Without supervision, a person may perform elementary work of the type described in section 14.6.15 on page 326 on an air operator's aircraft if that person has satisfactorily completed training for the task under a formal training programme and has previously performed the task under the direct supervision of an AME.

14.8 TSB of Canada

The Transportation Safety Board of Canada (TSB) is described in the GEN section of the Aeronautical Information Manual (AIM). It was established under the Canadian Transportation Accident Investigation and Safety Board Act (1989) to investigate aircraft accidents or incidents with the aim of preventing a recurrence. It is not the role of the TSB to apportion blame or liability.

The TSB has its headquarters in Gatineau, Québec and regional offices covering Pacific, Western, Central, Ontario, Québec and Atlantic parts of Canada.

The subjects of TSB investigations are "reportable aviation accidents" and "reportable aviation incidents". These are defined as follows.

A **reportable aviation accident** is an accident arising from the operation of an aircraft which results in a person sustaining serious injury or being killed, the aircraft sustaining structural damage or the aircraft being reported missing.

A **reportable aviation incident** applies only to aircraft having a maximum certified takeoff mass of 5700 kg or more. Reportable incidents include an engine failing or being shut down, smoke or fire, difficulties in controlling the aircraft, running off the runway or taxiway, a crew member becoming incapacitated, depressurisation, a fuel shortage requiring a diversion, the aircraft being fuelled with the incorrect or contaminated fuel, a collision[12] or loss of separation, an emergency declared from the aircraft or dangerous goods released in or from the aircraft.

[12]It is not clear why a collision would be treated as an incident rather than an accident. According to a TSB representative, the way that the terms *incident* and *accident* are applied by staff is that, if a collision, a risk of collision or a loss of separation occurs, and the aircraft sustains damage or failure that adversely affects the structural strength, performance or flight characteristics of the aircraft and that requires major repair or replacement of any affected component part, then it is a "reportable aviation accident". It would be very rare that a collision would not result in damage. The same holds true for any incident, for example, if an engine fails and the aircraft lands safely, it is an incident; if it crashes, then it is an accident.

The pilot-in-command, operator, owner or any crew member of a Canadian-registered aircraft involved in an accident or incident must report it to the TSB, whether the aircraft was operating inside or outside Canada. If the accident or incident occurred outside Canada then whatever reports are required by the foreign country must also be made.

The TSB also operates the *SECURITAS* programme which can be accessed at `http://www.tsb.gc.ca/eng/securitas/index.asp`. This used to be called *CARSP* and is intended for pilots to make confidential reports of incidents and potentially unsafe acts and conditions. The staff operating the SECURITAS programme treat all reports confidentially and, where possible, draw safety lessons from the reports and publish these, in a form where the pilots cannot be identified, for the benefit of other pilots and flight crew.

14.9 Air Traffic Services

Information about Air Traffic Services and Procedures can be found in the *Rules of the Air and Air Traffic Services* (RAC) section of the Aeronautical Information Manual (AIM). For convenience, the main points of the sections required for the Transport Canada written examination are summarised here.

14.9.1 Air Traffic & Advisory Services

NAV CANADA provides a range of air traffic services through its area control centres, area control units and control towers. In particular a pilot flying VFR will be given information about severe weather, navigation aids failing or recovering, airport conditions, reports of bird activity and other safety information. When this sort of information is provided to a pilot, the responsibility for deciding what action to take remains with the pilot-in-command and this is emphasised by the controller prefixing any suggestion with "ATC suggests..."

14.9.2 Flight Service Stations

See section 5.1.1 on page 93.

14.9.3 Radar Service—Clock Position System

In these days of digital watches, it is perhaps useful to remind pilots of the meaning of the "clock" positions used by ATC when telling a pilot of the position of another aircraft. *12 o'clock* is the position straight ahead on the track seen on ATC's radar display. *3 o'clock* is directly to the right, *6 o'clock* directly behind

and *9 o'clock* directly to the left. Note that the controller cannot determine the heading of the aircraft, only its track, and so, if you are crabbing 20° to the left, traffic called at your 2 o'clock would appear to be at your 3 o'clock position—for this reason always scan the sky a few degrees either side of the position given by the controller.

14.9.4 Clearances & Instructions

Unless ESCAT is invoked (see section 14.6.10), ATC may only issue clearances and instructions to aircraft in controlled airspace. If you are given a clearance which you do not understand or with which you cannot comply (normally for reasons of flight safety—e.g., a vector that would take you into cloud when flying VFR) then *do not read it back*. Reading it back indicates that you have accepted it. Instead, immediately tell the controller why you cannot accept it.

Normally a simple "Wilco" is sufficient from a VFR pilot to tell the controller that you have received his or her transmission and are intending to comply. The only clearances that you *must* read back are ones containing hold short instructions. These may be taxi clearances or landing clearances when *land and hold short operations* are in operation:

ATC: Papa Hotel Victor, cleared to land runway 25, hold short of runway 32

or taxi instructions:

Ground Control: Papa Hotel Victor, taxi bravo, left onto foxtrot, hold short of runway 32

14.9.5 Wake Turbulence Separation

Wake turbulence occurs behind and below any aircraft; its causes are described in section 11.7 on page 250. When considering the minimum distance by which controllers must separate aircraft, three categories are considered: heavy, medium and light, as defined in figure 14.9. Controllers must then vector any aircraft behind and up to 1,000 ft below a heavy and any light aircraft behind a medium, as shown in figure 14.9.

When the controller does not have radar to allow him or her to assess separation distance, at least 2 minutes is required after the departure of a heavy aircraft before the next aircraft can be released onto any runway within 2,500 ft of the runway used by the heavy.

A takeoff clearance is sometimes delayed because of wake turbulence considerations. The pilot of a delayed VFR aircraft may waive the wake turbulence requirement:[13]

[13]Note: the controller cannot suggest or initiate this waiver—it must come from the pilot.

Group	Definition (max takeoff mass)	Behind Heavy	Behind Medium
Heavy	$\geq 300,000$ lbs	4 miles	
Medium	12,501 to 299,999 lbs	5 miles	
Light	$\leq 12,500$ lbs	6 miles	4 miles

Figure 14.9: Wake Turbulence Separations

Pilot: Tower, Foxtrot Papa Tango November on foxtrot ready to go three two.

Tower: Papa Tango November taxi to position on 32 and hold for wake turbulence from departing A320.

Pilot: Papa Tango November waives wake turbulence separation

Tower: Roger, Papa Tango November cleared for takeoff runway 32, ...

The pilot cannot waive wake turbulence separation when departing from further down the runway than the aircraft causing the turbulence, when departing from the same runway but in the direction opposite to that of the aircraft causing the turbulence or when departing after a heavy aircraft has made a low approach and an overshoot on the departure runway.

Naturally a prudent pilot will only waive wake turbulence separation when he or she can be sure that any wake turbulence can be avoided—normally by rotating before the point at which the heavy rotated and then being able to fly away from the turbulence.

On landing, minimum radar separations are also applied. However, a tower controller can pass responsibility for avoiding the wake turbulence to a pilot by issuing a warning of the form: "Papa Tango November, follow the Airbus on short final, you are number two, caution wake turbulence." If you accept this type of clearance then you automatically assume all responsibility for wake turbulence avoidance.

14.9.6 Uncontrolled Aerodrome Operations

An uncontrolled aerodrome is one without a control tower. Some uncontrolled aerodromes are within a Mandatory Frequency zone (see section 14.6.7) and other uncontrolled aerodromes have an allocated Aerodrome Traffic Frequency (ATF). In the absence of both of these, the frequency of 123.2 MHz should be used to broadcast to traffic in the area.

The traffic circuit for an uncontrolled aerodrome is illustrated in figure 14.10 and has the following characteristics:

Departures. When departing you must climb on runway heading until you reach the circuit altitude (typically 1,000 ft above ground) before turning *en route*. However, you should not turn back over the aerodrome until you are at least 500 ft above the circuit altitude.

Arrivals—no Mandatory Frequency. You should join the circuit from the upwind side. If you can "confirm without doubt that there is no conflicting traffic" then you may alternatively join the circuit straight into the downwind leg but, since there may be aircraft in the circuit without radios, it is almost impossible to confirm the absence of conflicting traffic—joining from the upwind side is always the better option. Unless stated otherwise in the Canada Flight Supplement, all turns in the circuit should be made to the left.

Arrivals—Mandatory Frequency Zone. You may join the circuit at an uncontrolled aerodrome within a Mandatory Frequency (MF) Zone straight into the downwind leg, at 45° to the downwind leg, straight into the base leg or straight into the final leg.

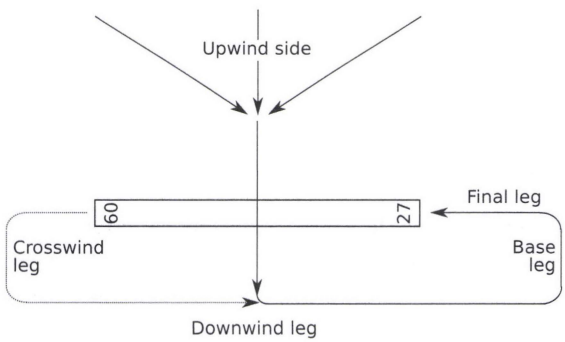

Figure 14.10: The Circuit at an Uncontrolled Airport

Anecdote 67 *Many airports in MF zones are staffed, at least for most of the daytime hours. This is particularly useful in Québec where some pilots may be broadcasting in French, others in English; having a person on the ground to translate can be very useful. However, some MF airports have only a UNICOM, which may often be unstaffed. Trois-Rivières is such an airport and I was following a friend's aircraft approaching from the east one day when a pilot, transmitting in French, said that he was on straight-in final—something that is permitted in an MF zone. I knew that my friend in the leading aircraft spoke no French, and it was only my wife's command of French and a call we made to the aircraft ahead that avoided a potentially serious conflict.*

VFR pilots often give way to commercial and larger IFR aircraft but this is purely a courtesy—these types of aircraft do not have any special priority.

14.9.7 Controlled Aerodrome Operations

The traffic circuit for a controlled aerodrome is effectively the same as the one shown in figure 14.10 for uncontrolled aerodromes except that when approaching to land you may be *instructed* to enter straight into the downwind leg, at 45° to the downwind leg, straight into the base leg or straight into the final leg.

Departures. At controlled aerodromes a takeoff clearance is required before departure. If the term "immediate" is used in the takeoff clearance then you must taxi straight onto the runway and start your takeoff roll without pausing. If this is not possible then do not accept such a takeoff clearance. When you have left the control zone you do not need permission from ATC to change radio frequency. In the case of aircraft with no radios, the visual light signals listed in figure 14.11 may be used from the tower.

Anecdote 68 *I am red/green colour blind, and therefore may not fly at night and may not fly into a control zone without a two-way radio. When I queried the night prohibition, I was told that it was because I might lose my radios when flying in a control zone at night and not be able to decode the light signals. Given that 1 in 20 men are red/green colour blind, it seems incredible that some other scheme for light signals has not be found: perhaps flashing a white light with different cadences or perhaps using colours that are not easily confused (white, red, blue). But none of these suggestions seem to be acceptable.*

Arrivals. At controlled aerodromes, except for aircraft without radios that have previously arranged their arrival by telephone, it is necessary to have a landing clearance before landing. Once the aircraft is on the ground, unless instructed otherwise by ATC, you are expected to leave the runway on the first convenient taxiway and taxi forward across the hold-short lines (or 200 ft from the runway if there are no hold-short lines). In cases of radio failure, the tower may use the light signals listed in figure 14.11.

To expedite traffic, at aerodromes with intersecting runways ATC may operate *Land and Hold Short Operations* (LAHSO) if the weather conditions are

Signal	On Ground	In the Air
Series of green flashes	Cleared to taxi	Return for landing
Steady green light	Cleared for takeoff	Cleared to land
Series of red flashes	Taxi clear of landing area in use	Airport unsafe: do not land
Steady red light	Stop	Give way: continue circling
Flashing white light	Return to starting point	
Blinking runway lights	Vehicles and pedestrians to leave runway	

Figure 14.11: Visual Signals

appropriate—1,000 ft ceilings, visibility at least 3 statute miles, good braking conditions on the runway, no snow or ice, no tailwind over 5 knots. The landing clearance then includes the instruction to "hold short of runway X". In this case, even if you are flying VFR, you must read back the landing clearance including the hold short instruction. If you do not believe that you can comply with the hold short instruction then you must not accept the clearance; instead use the term "unable".

14.9.8 VFR *En Route* Procedures

When flying VFR and not communicating with ATC you should monitor 126.7 MHz and 121.5 MHz. In many parts of Canada 126.7 MHz has become congested due to continuous, and often unnecessary, informal position reporting by VFR aircraft—see section 11.3.2. Formal VFR position reports are very useful when on cross-country flights, and should be made to a Flight Service Station using the format on the back of paper copies of the CFS. An example is given in section 6.4.8 on page 125.

When *en route* on a VFR flight plan in an area with radar coverage, you may request ATC's "radar surveillance" service, informally known as *Flight Following*. If ATC's workload permits, you will be supplied with a transponder code and again, if workload permits, traffic in your area will be pointed out to you. However, it is important to realise that having flight following does not remove the need to look out for, and avoid, other aircraft and terrain.

14.9.9 VFR Holding Procedures

VFR pilots may be asked to "hold" by making 360° turns around a visual reference point. For the convenience of the pilot, normally seated on the left-hand side of the aircraft, it is usual to fly left-hand circles although this is not mandatory.

14.9.10 Dangerous Goods

There are nine classes of dangerous goods and these may not be carried on board any Canadian aircraft or foreign aircraft in Canadian airspace unless in compliance with the *Transportation of Dangerous Goods Act, 1992* and the *Transportation of Dangerous Goods Regulations*. The latter document incorporates the *ICAO Technical Instructions for the Safe Transport of Dangerous Goods by Air*.

The classes of dangerous goods are:

Class 1: explosives

Class 2: gases

Class 3: flammable liquids

Class 4: flammable solids: substances liable to spontaneous combustion; substances which, in contact with water, emit flammable gases

Class 5: oxidising substances: organic peroxide

Class 6: toxic and infectious substances

Class 7: radioactive material

Class 8: corrosives

Class 9: miscellaneous dangerous goods and articles

Any employee of an air operator who is obliged to handle dangerous goods must be trained every 2 years under a *Transportation of Dangerous Goods Training Programme* approved by Transport Canada.

14.10 International Flight

The Facilitation (FAL) section of the Aeronautical Information Manual (AIM) contains details of the procedures to be used when entering, leaving or transiting Canadian airspace. The regulations are

different for private and commercial flights and only private flights are treated below.

A flight plan must be filed for all transborder flights.

When flying into Canada you must land at an authorised Aerodrome of Entry as indicated in the Canada Flight Supplement and you must ring Canada Customs between two and forty-eight hours before the estimated time of landing.[14] Canada Customs can be reached by telephone on 1-888-CAN-PASS in most of the USA. If you have to land at an airport different from the one planned (e.g., because of mechanical difficulties or weather issues) then you must call 1-888-CAN-PASS or the nearest RCMP office as soon as possible after landing.

Canada Customs operates a programme called CANPASS where individuals may register their details in advance and be issued with a CANPASS certificate. If all the crew and passengers in an aircraft arriving in Canada have CANPASS certificates then there is a wider range of aerodromes available for entry.

The are no special (Canadian) regulations regarding flights leaving Canada for a foreign state.

14.11 Answers to Exercises

Exercise 103

The section digit of the section number is a 2 indicating that this is a standard. Any associated advisory would have section number 343 and the underlying regulation has section number 303.

Exercise 104

An airway starts at 1,200 ft above ground. As there is no designated airspace in the area, and as the airway will not start until 1,200 ft AGL (i.e., 2,200 ft ASL), at 1,800 ft ASL the airspace will be class G: uncontrolled.

By 5,000 ft ASL we are in the airway and so the airspace is class E: controlled. This is also true of 10,000 ft ASL.

However, at 12,500 ft ASL, as there is controlled airspace below, class B airspace will begin. So at 14,000 ft ASL the airspace is class B. This continues up to 18,000 ft ASL, where the airspace becomes class A (up to FL 600). At 21,000 ft ASL, the airspace will be class A.

Exercise 105

Yes. The weather conditions at the departure airport need not be taken into account when selecting to fly VFR OTT. The forecast conditions at the destination airport appear to meet the required conditions although the appropriate section of the CARs specifies "a sky condition of scattered cloud or clear": it does not mention FEW clouds, the condition that lies between scattered and clear.

Exercise 106

Yes, because a Cessna 172 is an unpressurised aircraft, removal and replacement of the door is explicitly permitted.

[14] It used to be possible to enter ADCUS (advise customs) on a flight plan form and assume that Canada Customs would be informed—this has not been possible for many years.

Appendix A

Acronyms Used in this Text

Aviation is full of acronyms, and some of those used in this book are listed below.

AC: Alternating Current (section 13.1.2)

ACAC: Air Carrier Advisory Circular (page 232)

ADCUS: Advise Customs (page 335)

ADF: Automatic Direction Finder (section 7.6)

ADIZ: Air Defence Identification Zone (section 14.6.10)

ADS-B: Automatic Dependent Surveillance-Broadcast (section 10.4.2)

AFM: Aircraft Flight Manual (page 231)

AGL: Above Ground Level

AHRS: Attitude and Heading Reference System (section 10.5.1)

AI: Attitude Indicator

AIC: Aeronautical Information Circular

AIM: Aeronautical Information Manual

AIRMET: Airman's Meteorological Advisory (section 5.4.6)

AME: Aircraft Maintenance Engineer

AMO: Approved Maintenance Organisation

AoA: Angle of attack (section 9.2.6)

AOPA: Aircraft Owners and Pilots Association

APU: Auxiliary Power Unit

ARP: Aerospace Recommended Practice (section 1.7.2)

ASI: Airspeed Indicator (section 10.1.2)

ASL: Above Sea Level

ATC: Air Traffic Control

ATF: Aerodrome Traffic Frequency

ATIS: Automatic Terminal Information Service (section 5.1.5)

AVGAS: Aviation Gasoline (section 13.4)

AVTUR: Jet A-1 (section 12.3.7)

AWBS: Aviation Weather Briefing Service (section 5.1.2)

AWIS: Aviation Weather Information Service (section 5.1.1)

AWOS: Automated Weather Observation Station (page 94)

AWWS: Aviation Weather Web Site

BFO: Beat Frequency Oscillator (section 7.6)

BPR: Bypass ratio (of a turbine) (section 12.3.3)

CAA: Civil Aviation Authority

CAP: Canada Air Pilot

CAPPI: Constant Altitude Plan Position Indicator (section 5.3.3)

CARs: Canadian Aviation Regulations

CAS: Calibrated Airspeed (section 10.1.2)

CAT: Clear Air Turbulence (section 4.13.4)

CDI: Course Deviation Indicator (section 7.4)

CFIT: Controlled Flight into Terrain (section 1.5.3)

CFS: Canada Flight Supplement

CHT: Cylinder Head Temperature (section 12.4.12)

CPL: Commercial Pilot Licence

CRFI: Canadian Runway Friction Index (section 11.8.2)

CRM: Crew Resource Management (section 1.9.1)

DC: Direct Current (section 13.1.2)

DECIDE: Model by Benner (section 1.6.2)

DED: Deduced

DME: Distance Measuring Equipment (section 7.8)

DRCO: Dialled Remote Communications Outlet

DVOR: Doppler VOR (section 7.4)

EAA: Experimental Aircraft Association

EGT: Exhaust Gas Temperature (section 12.4.12)

ELT: Emergency Locator Transmitter (section 11.9)

EMC: Electromagnetic Compatibility (section 11.1.6)

EMI: Electromagnetic Interference (section 13.1.9)

ESCAT: Emergency Security Control of Air Traffic (section 14.2.1)

ESDU: Formally "Engineering Standards Data Unit" (section 4.6.11)

ETA: Estimated Time of Arrival (section 8.2.3)

EWH: Eye to Wheel Height (page 233)

FAA: Federal Aviation Administration (of USA)

FADEC: Full Authority Digital Engine (or Electronics) Control (section 12.3.6)

FBO: Fixed Base Operator: a company providing fuelling and other services to pilots at an airport

FCC: Federal Communications Commission

FD: Upper Winds Forecast (section 5.4.3)

FIC: Flight Information Centre (section 5.1.2)

FIR: Flight Information Region (page **??**)

FL: Flight Level

FSII: Fuel System Icing Inhibitor (section 13.4.1)

FSS: Flight Service Station (section 5.1.1)

GBAS: Ground-Based Augmentation System (section 7.3)

GFA: Graphical Area Forecast (section 5.4.1)

GNSS: Global Navigation Satellite System (section 7.3)

GPS: Global Positioning System (section 7.3)

GPWS: Ground Proximity Warning Systems (section 10.5.2)

HF: High Frequency

Hg: Mercury

HI: Heading Indicator

HIRF: High-Intensity Radiated Field (section 4.15.4)

HSI: Horizontal Situation Indicator (section 7.5)

IAS: Indicated Airspeed (section 10.1.2)

ICAO: International Civil Aviation Organisation

ICRP: International Commission on Radiological Protection (section 2.6)

IFR: Instrument Flight Rules

ILS: Instrument Landing System: ground-based transmitters that provide runway centreline and glideslope information to a landing aircraft

IMC: Instrument Meteorological Conditions

INS: Inertial Navigation System

ISA: International Standard Atmosphere (section 4.2.2)

IVSI: Instantaneous Vertical Speed Indicator (section 10.1.3)

JAA: Joint Aviation Authorities

JBD: James Brake Decelerometer (section 11.8.2)

JBI: James Brake Index (section 11.8.2)

KIAS: Knots Indicated Airspeed

LAAS: Local-Area Augmentation System (page 134)

LAHSO: Land and Hold Short Operations (section 14.9.7)

LEO: Low Earth Orbit (satellite) (section 10.4.2)

LIDAR: Light Detection and Ranging

LRI: Lift Reserve Indicator (section 10.1.2)

LWIS: Limited Weather Information System (page 94)

MDA: Minimum Descent Altitude

MEL: Minimum Equipment List

MEMS: Microelectromechanical System (section 10.5.1)

METAR: Aviation Routine Weather Report (section 5.3.2)

MOCA: Minimum Obstacle Clearance Altitude

MOGAS: Motor Gasoline (section 13.4)

MRA: Minimum Reception Altitude

MTOM: Maximum Takeoff Mass (page 250)

NACA: National Advisory Committee for Aeronautics (section 9.3.2)

NASA: National Aeronautics and Space Administration

NDB: Non-Directional Beacon (section 7.6)

nm: Nautical Miles (or, on page 224, nanometres)

NOAA: National Oceanic and Atmospheric Administration (USA)

NOTAM: A notice containing information concerning the establishment, condition or change in any aeronautical facility, service, procedure or hazard, the timely knowledge of which is essential to personnel concerned with flight operations (section 6.4.3)

NSS: National Search and Rescue Secretariat (section 11.9)

OBS: Omni-Bearing Selector (section 7.4)

OTT: Over-the-top (as in "VFR OTT")

PAPI: Precision Approach Path Indicator (section 11.2.3)

PBN: Performance-Based Navigation (section 7.1)

PFD: Primary Flight Display (figure 10.7)

PIC: Pilot-in-Command

PIREP: Pilot Report of Conditions (section 5.3.4)

POH: Pilot Operating Handbook

PPL: Private Pilot Licence

PSI: Pounds-force per square inch

Q850: A decision-making process (section 1.6.3)

RADAR: Radio Detection and Ranging (section 10.5.2)

RAIM: Receiver Autonomous Integrity Monitoring (section 7.3.6)

RAT: Ram Air Turbine (section 13.5.2)

RCO: Remote Communications Outlet

REM: Rapid Eye-movement Sleep (section 2.8)

RFI: Radio Frequency Interference (section 13.1.9)

RMI: Radio Magnetic Indicator (section 7.7)

RNP: Required Navigation Performance (section 7.1)

RVR: Runway Visibility Range

SA: Situational Awareness (section 1.5.3)

SAE: Society of Automotive Engineers (section 1.7.2)

SAR: Search and Rescue (section 11.9)

SARPS: Standards and Recommended Practices (section 1.7.2)

SCATANA: Security Control of Air Traffic and Navigation Aids (section 14.2.1)

SCUBA: Self-Contained Underwater Breathing Apparatus (section 2.2.11)

SF: Student Flying (section 1.9.1)

SIGMET: Significant Meteorological Information (section 5.4.5)

Skew-T: A report or forecast on atmospheric conditions (Skewed Temperature) (section 5.4.4)

SNF: Student Not Flying (section 1.9.1)

SOP: Standard Operating Procedures (section 1.8.2)

SPPR: Single Point Pressure Refuelling (section 13.4.2)

STAMP: Systems-Theoretic Accident Model and Processes (section 1.4.3)

STOL: Short Takeoff and Landing

SWS: Slow-Wave Sleep (section 2.8)

TACAN: Tactical Air Navigation Transmitter (section 7.4)

TAF: Terminal Area Forecase (section 5.4.2)

TAS: True Airspeed (section 10.1.2)

TCAS: Traffic Collision Avoidance System (section 10.4)

TMG: Track Made Good (section 8.2.4)

TSB: Transportation Safety Board (section 14.8)

UK: United Kingdom of Great Britain and Northern Ireland

USA: United States of America

UTC: Co-ordinated Universal Time (section 6.2.4)

VASIS: Visual Approach Slope Indicator System (section 11.2.3)

VFR: Visual Flight Rules (section 14.6.8)

VHF: Very High Frequency

VMC: Visual Meteorological Conditions

VNC: VFR Navigation Chart (section 6.3)

VOR: Very-High Frequency Omnidirectional Range (section 7.4)

VORTAC: A system comprising a VOR and colocated tactical air navigation system (section 7.4)

VOT: VOR Test Facility (section 7.4)

VTA: VFR Terminal Chart (section 6.3)

WAAS: Wide-Area Augmentation System (page 134)

WAC: World Aeronautical Chart (section 6.3)

WMO: World Meteorological Organisation

Appendix B

Human Factors Dialogues

The dialogues in this appendix are included as examples that can be analysed using the techniques outlined in chapter 1, either individually or in ground school discussion.

B.1 Dialogue 1

Consider the layout of Providence, Rhode Island, shown in figure B.1. The following incident took place there on 6th December 1999 when the cloud was so low that the tower was in cloud and runway 5R category II ILS was in operation. A USAirways flight had just landed and was taxiing to the gate and a USAirways 737, flight 2998, was preparing for takeoff and holding short of 5R on taxiway Sierra behind a FedEx flight which was rolling onto the runway.

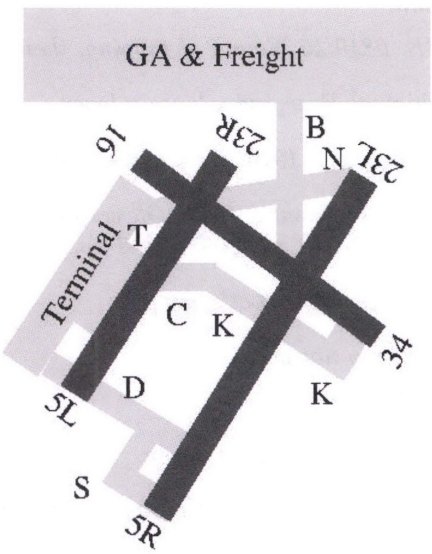

Figure B.1: Providence, Rhode Island

United flight 1448 had just landed and rolled out on runway 5R. It was cleared to the gate via November and Tango and was instructed to report crossing runway 16.

As flight 1448 was taxiing, the FedEx flight was cleared for takeoff. As it rotated, flight 1448 reported:

1448 is on November, by the runway here. We don't see the ahhh... are we cleared straight ahead on November?

The controller was working both tower and ground and confirmed the instruction, assuming that flight 1448 was on November about the cross 16/34 and 23R/5L. In fact flight 1448 was lost and had turned left on Bravo, crossed onto runway 16/34 and had come to a stop at the intersection of 23L/5R and 16/34.

Shortly afterwards flight 1448 made the call:

And ah United 1448... we're approaching Kilo here... and... ah... ah somebody just took off...

In the background of the transmission, the roar of FedEx's departure can be heard.

Tower: *United 1448, you shouldn't be anywhere near Kilo. Hold your position, please, just stop.*

United 1448: *Tower, this is United 1448, we are currently on a runway. I am looking out to the right at Kilo... we need to go onto the Kilo taxiway.*

Tower: *United 1448, you were supposed to taxi November and Tango, I need to know what runway you're on. I can't see anything from the tower.*

United 1448: *Ma'am, we are on 23R, intersection of 16. We did not connect on November, we are... we are by Kilo to our right... we just overshot Kilo, we did not see it.*

Tower: *United, standby please. USAir 2998, runway 5R, fly runway heading, cleared for takeoff.*

United 1448: *Ma'am, I'm trying to advise you we are on an active runway. United 1448.*

Tower: *23R is* not *an active runway, it's a taxiway when we're IFR or in the dark.*

Upon hearing this USAir 2998 declines to accept the takeoff clearance, advising the tower that it will remain clear of all runways until the lost United jet is located. This appears to make the tower controller even more irritable.

Tower: *Everybody standby please, radio silence until I talk to you.*

United 1448: *This is United 1448, we're on 23R, we're looking at Kilo straight ahead, if we can go straight we can get on Kilo and get off the runway.*

Tower: *United 1448, standby, don't talk! I have other things I need to do...*

United 1448: *Roger, ma'am*

Tower: *USAir 2998, runway 5 right, fly runway heading, cleared for takeoff.*

USAir 2998: *Tower, USAir 2998, 'til we figure out what's going on down there, we're just gonna stay clear*

of all runways.

The tower controller acknowledges this and telephones the radar controller handling departures: "*USAir 2998 isn't going yet because I have a United who doesn't know where the hell he is. Take him back and I'll flash you when he's ready.*"

Tower: *United 1448, understand you're on runway 23R, have you gone past taxiway Kilo and Tango?*

Finally, the tower controller stops all departures and all traffic movements on the surface. Then she locates flight 1448 which, making one final taxi error which leads it to the threshold of runway 34, manages to reach the terminal area.

B.2 Dialogue 2

Consider the following incident of a Continental Airlines DC-9 arriving from Washington, D.C. descending toward Houston.

The first officer was the pilot flying. As the aircraft descended through FL190, he called for the in-range checklist. There are seven items on this checklist:

1. fuel boost pumps
2. No Smoking and Seat Belt signs
3. flight instruments and altimeters
4. hydraulics to high pressure
5. shoulder harness
6. approach briefing
7. sterile cockpit light.

The following transcript covers the period from the in-range checklist to the eventual "landing" at Houston.

FO: *In-range check please.*

TIME: 0845:31

CAP: *ooh, ooh, ooh...[laughter] Uh, boost pumps we got. Number four is on.*

FO: *No.*

CAP: *Number four, on. Number one, one, two, three. Whatever that is. They're on and checked. No smoke seat belts on. Flight instruments and altimeters? Checked, set. Shoulder harness on.*

FO: *On.*

CAP: *Approach briefing? Why did they remove the sterile cockpit off of here but they left it on here?*

FO: *I, gotta go to ... 13,000, right, not ten?*

CAP: *Correcto... Correcto.*

ATC: *Continental 1943, say speed.*

CAP: *All right, now doing 310. What do you need?*

ATC: *That will be fine.*

ATC: *Continental 1943, descend and maintain 10,000.*

CAP: *Down to ten, Continental 1943.*

FO: *Actually he said descend to 10,000 but he didn't say cross Daisetta at ten.*

CAP: *That's correct ... El correcto.*

FO: *We'll be there anyhow.*

CAP: *Come on, if you keep this bumpy I'm going to have to *** ... I was doin' all right until you started this.*

FO: *I thought, I thought you had a pretty good bladder, I thought ... ****

CAP: ***** two cups of coffee.*

[Sound of altitude alert]

FO: *Damn.*

TIME: 0849:45 [Sound of tapping, then whistling]

CAP: [singing] *Everybody, loves a lover...*

ATC: *Continental 1943, fly heading 220.*

CAP: *220, Continental 1943. Oh very well, we can do that too ... Got everybody lined up pretty well there.*

FO: *Boy, I guess so. Let's see, 26.*

CAP: *We may not get it.*

[Sound of altitude alert]

CAP: *One to go, eight for seven.*

OTHER AIRCRAFT: *Continental 1989, 270, down to seven.*

ATC: *I'll Pass your request on.*

CAP: *Pass it on, pass it on, pass it on. We'll be gone, we'll be gone, we'll be gone.*

TIME: 0854:49

FO: *Approach check please when you're ready.*

CAP: *Ah, yes, ah ... altimeters and the bugs?*

FO: *967 set right and 132 set right.*

CAP: *VOR, ADF switches?*

[Sound of altitude alert]

CAP: *Set VOR, ADF whatever ... Marker's on.*

FO: *Five for four.*

CAP: *Glideslope's alive. Radios are ident ****

FO: *We'll go manual spoilers.*

CAP: *Oh, very well.*

FO: *Forty flaps.*

CAP: *Forty flaps?*

FO: *Roger dodger... ***, you scared me half to death.*

CAP: *I'm just tryin' to ... *** mode selector...yeah and *** two lights *** and that's not going to change much. I'll just leave it there.*

ATC: *Continental 1943, 13 miles from the marker, maintain 2,000 til established on the localizer, cleared ILS 27 approach.*

CAP: *2,000 til established, cleared for 27 approach, Continental 1943.*

FO: *I'm going to intercept the glidepath up here ...Tanks is at six.*

CAP: **** Crummy weather, what's this? *** how can I play tennis if it's raining?*

ATC: *Continental 1943, on your speed, 190 or faster to the marker and contact the tower 125.35.*

CAP: *25.35, Continental 1943. Okay.*

FO: *They're out of the way, huh?*

CAP: *You've been up all night too. We're about ten miles outside the airport. Flight attendants be seated for arrival.*

[Sound of landing gear warning horn]

CAP: *Continental 1943 with you for 27.*

TWR: *Continental 1943, Houston tower. Runway 27, cleared to land, wind 240 at seven.*

CAP: *Cleared to land 27, Continental 1943.*

FO: *Cleared to land.*

CAP: *Cleared to lando ....Now. where was I, ahh, b-b-b-b-b-b-aaaaaah. air conditioning auto shutoff is armed, briefing has been made. Approach check is completed.*

[Sound of altitude alert]

CAP: *Cleared to lando.*

FO: *Cleared to land.*

CAP: *Aw shoot, I can't play tennis when it's like this. Well, maybe this afternoon it'll clear up. Actually I've still got a lot of time.*

FO: *Go slats and five.*

CAP: *Slats are going to five. I was watching the news this morning and they said it was going to be nice out. They lied. Look at the ground, it doesn't look like much rain. It's overcast.*

FO: *Dismal.*

CAP: *That's not too bad. We don't worry about.*

FO: *Yeah. *** might be rather pleasant. 190 to the marker.*

CAP: [Sound of whistling]

FO: *The middle marker?*

CAP: *To Tanks.*

FO: *190 to the middle marker or to Tanks?*

CAP: *Tanks *** whatever you want ... Runway in sighto.*

FO: *There's Tanks ... so, flaps 15.*

CAP: *I think the flaps...*

[Sound of landing gear warning horn]

CAP: *Well, we know that, you want the gear.*

FO: *Gear down.*

[Sound of altitude alert and thump of gear handle going down]

FO: *Landing check, 25 in the green.*

[Sound of landing gear warning horn starts and continues]

FO: *Flaps 40.*

FO: *Here comes 50.*

CAP: *Fifty flaps.*

FO: *I don't have any flaps.*

CAP: *****

FO: *Want to take it around?*

CAP: *No, that's all right. Keep your speed up here about...*

[Sound of landing gear warning horn stops briefly.]

FO: *I can't slow it down here now.*

CAP: *You're all right.*

FO: *We're just smokin' in here.*

[Sound of GPWS warning: whoop whoop pull up, whoop whoop pull up, whoop whoop pull up. Sound of landing gear warning horn starts and continues.]

FO: *Want to land it?*

CAP: *Yeah.*

FO: *Your airplane. Captain's airplane. You want it?*

CAP: *Yeah.*

[Sound of impact. Loud rattling and rumbling starts and continues]

CAP: *Tower, 1943 on Runway 27 needs some help.*

[Rattling and rumbling ends after 31 seconds.]

The aircraft touched down at 190 knots with its landing gear up and slid 7000 feet down the runway and then onto the grass. There was no fire and there were no deaths or serious injuries.

How did the following circumstances contribute to the accident?

The First Officer had been the subject of a professionally damaging complaint by a previous Captain for insubordination.

The designers of the DC-9 used separate controls for the hydraulic pressure and the landing gear and activating the landing gear did not automatically raise the hydraulic pressure.

The Captain appeared to be suffering from fatigue, and a full bladder.

Although the gear warning horn sounded for most of the approach, neither pilot heard it and acted on it.

There was no sterile cockpit.

There were no challenge-response techniques.

B.3 Dialogue 3

Consider the following example of an American Eagle Jetstream arriving at Raleigh-Durham (KRDU) after a short and uneventful flight. The aircraft had been cleared to the Final Approach Fix at or above 2100 feet for the ILS approach several miles behind a Boeing 727.

The captain, who was pilot flying, suddenly called for an increase in prop speed and then said to the first officer, "Why's that ignition light on? We just had a flameout?"

FO: *I'm not sure what's goin' on with it.*

TIME: 1833:38

CAP: *We had a flameout.*

Low-frequency beat of out-of-sync props begins and continues for eight seconds

FO: *'K, you got it?*

CAP: *Yeah.*

FO: *We lose an engine?*

CAP: *OK, yeah ... OK, uh.*

FO: *I'm gonna turn that ...*

CAP: *See if that, turn on the auto.*

FO: *I'm goin' to turn on, both uh ... ignitions, OK?*

CAP: *OK.*

FO: *We lost that en... left one?*

CAP: *Yeah.*

FO: *Whatta you want me to do, you gonna continue?*

CAP: *OK, yeah, I'm gonna continue.*

FO: *All right, I'm gonna...*

TIME: 1834:03

Sound of low-frequency beat begins and continues for three seconds

CAP: *Let's go missed approach.*

FO: *All right.*

Sound of stall warning horn for 0.7 second

CAP: *Set max power.*

Sound of stall warning horn for 0.3 second. Indicated airspeed is 100 knots, heading has drifted 60° to the left of the localiser.

FO: *Lower the nose, lower the nose, lower the nose.*

Sound of single stall warning horn starts, immediately followed by sound of dual stall warning horns

FO: *You got it?*

CAP: *Yeah.*

FO: *Lower the nose.*

Unidentified rattling sound

FO: *It's the wrong, wrong foot, wrong engine.*

The stall warnings stop; the prop beat begins and continues for four seconds; the stall warnings resume; there is a sound of heavy breathing

FO: *Here.*

The stall warnings stop, then resume. The aircraft loses 1200 feet in 8 seconds and the indicated airspeed rises from 100 to 200 knots. The aircraft's heading turns to 140° *from the localiser and there is the sound of impact*

Both crew and 13 passengers died, 5 passengers survived.

In fact, no engine failure had occurred; the illumination of the ignition light was a correct response to a momentary negative torque which occurred when the first officer brought the prop control levers to 100 percent while the power levers were at flight idle.

Investigators believed that the captain's error may have arisen from simulator training where an ignition light illuminating was normally associated with a flameout.

Following an engine failure, the correct response would have been for the non-flying pilot (the first officer in this case) to confirm the failure by advancing the power levers and checking for a response. The next action should have been to feather the prop on the failed engine.

The investigation found that the captain had a history of weak airmanship: he failed his second-in-command check at his previous airline in eight different areas, including judgement. A second captain had evaluated him following his successful completion of the check and had answered "no" to the question: "would you feel comfortable if you were a passenger and he was the captain?"

Appendix C

Navigation Calculators

Contents

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C.1 In the Examination Room

Transport Canada allows any calculator without a memory capable of storing text into the examination room. In addition, aviation calculators are allowed if they are on the list linked to from:

`https://tc.canada.ca/en/aviation/licensing-pilots-personnel/flight-crew-licences-permits-ratings`.

My recommendation is to take a simple, 4-function calculator for basic arithmetic, and a digital aviation calculator from the Transport Canada list for the more aviation-oriented calculations (calculation of pressure altitude, heading to fly, etc.).

Exam Hint 38 *Unless you have been brought up with slide rules, the manner of using an E6B analogue calculator can be difficult to remember, leading to errors. I would not advise the use of one in a written examination (or in the preparation for the flight test). Using an E6B is likely to take much longer and give less accurate results than using a digital calculator.*

Exam Hint 39 *Some of the digital, aviation calculators permitted by Transport Canada have user interfaces that are extremely counter-intuitive. Ensure that you are very familiar with the keystrokes needed to perform a particular calculation* before *you enter the examination room.*

C.2 Flight Planning

There are many applications for tablets, smartphones and laptops available for flight planning. These may be used for flight test preparation,[1] but not in a written examination.

Given the very wide range of flight planning applications, it is common for pilots to have an almost religious fervour for the one they happen to use. At the time of writing, perhaps the three most commonly-used applications are (in alphabetical order): FltPlan Go, ForeFlight and Garmin Pilot. Garmin bought FltPlan Go in August 2018, possibly with the intent of merging it with its Garmin Pilot product. An unbiased study of the usability of these three programs can be found in *A Usability Study for Electronic Flight Bag (EFB) Flight Planning Applications on Tablet Devices for Ab-initio Pilots* by Jeff Schwartzentruber.

During the life of this book, it is to be expected that other applications will emerge.

When looking for a flight planning application, the following features should be sought:

- Support for both Canadian and USA VFR and LO-Charts.
- A mechanism to allow a user to create a route by tapping on the screen and dragging sections to waypoints on the map.
- Automatic derivation of the winds aloft and the ability to advise on flight duration at different altitudes.
- Information about the destination and possible alternate airports: runway layouts, radio frequencies, FBOs, etc.
- Feedback from other pilots about the friendliness and efficiency of the FBOs.
- Ability to display and print a flight log.

In addition, some applications can file the flight plan for the route automatically.

[1] TP 13462 states: "Software or online flight planning may be used for the planning and generation of a navigation log."

C.3 Navigation in Flight

Once in the air, the navigation application becomes a moving map with the aircraft displayed flying across it. The current ground speed and time to next waypoint should be displayed continuously.

It is useful if the application can also display ADS-B IN information; see section 10.4.2 on page 220.

As the destination airport is reached, it is helpful if the application switches automatically to a runway view. Once on the ground, it should allow the pilot to see the aircraft travelling over the taxiway diagram.

Anecdote 69 *Having used these types of applications for many years, my main criticism is feature-creep. Like most software, more and more largely irrelevant features are being added in a feature war with other vendors. This is resulting in programs that are becoming unwieldy and taking too long to load and respond to key strokes. Some of the applications also rely on the users being able to distinguish between green and red icons, indicating whether the maps are current or out-of-date. One in twelve male pilots cannot distinguish between these colours on a tablet.*

C.4 The Analogue Calculator

I was brought up with analogue slide rules and find the E6B and its equivalent analogue devices great fun to use. They also allow a pilot to impress non-pilot friends! However, even I would never dream of using one in a written examination, and I can't remember the last time I used one in flight.

The E6B *can* be recommended for calculating ground speed if the aircraft is not equipped with a GPS and, for completeness and historical interest, I give an example here of how it can be used.

Assume that you have been flying for 28 mins and have covered a distance of 42 nautical miles. What is your ground speed?

It should be said that this can be calculated in seconds using a simple 4-function digital calculator ($\frac{42}{28} \times 60 = 90$), but here's how we used to do it.

Align the miles (42) on the outer scale with the time (28) on the inner scale as shown in figure C.1.

Look at where 1 hour (60 minutes) appears on the inner scale and read the distance that you will cover in an hour on the outer scale: 90 nautical miles in this case. You have been travelling at 90 knots for the last 42 nautical miles.

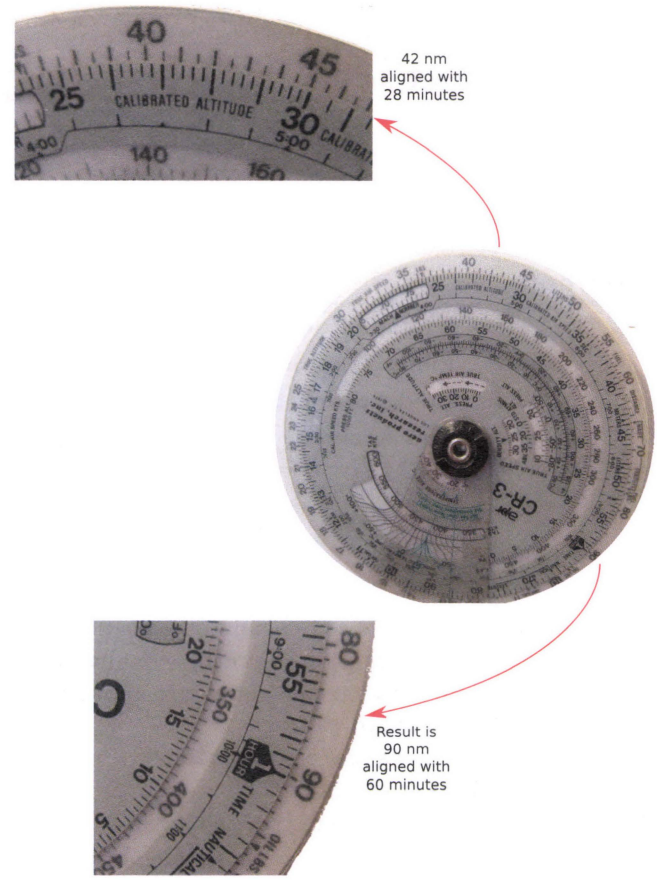

Figure C.1: Calculating Ground Speed

Assuming that your ground speed doesn't change much on each leg, it will be necessary only to move the inner wheel a small amount at each checkpoint.

Appendix D

Examination Technique: Linear Interpolation

Linear interpolation answers such questions as:

> *At 10° C the takeoff distance is 1,905 ft; at 20° C it is 2,060 ft. What is the takeoff distance at 18° C?*

As described in examination hint 24 on page 244, linear interpolation is a skill required more in the examination room than in practice. For example, if you are interpolating to find a takeoff distance at a particular temperature, then it is prudent simply to take the larger of the two numbers; in this example simply take 2,060 ft.

There are three ways of answering a question like the one above, and these are described in the sections below.

D.1 Method 1: Graphing

This is the most useful method for understanding the technique. It is, however, less accurate than the other methods and takes a lot longer.

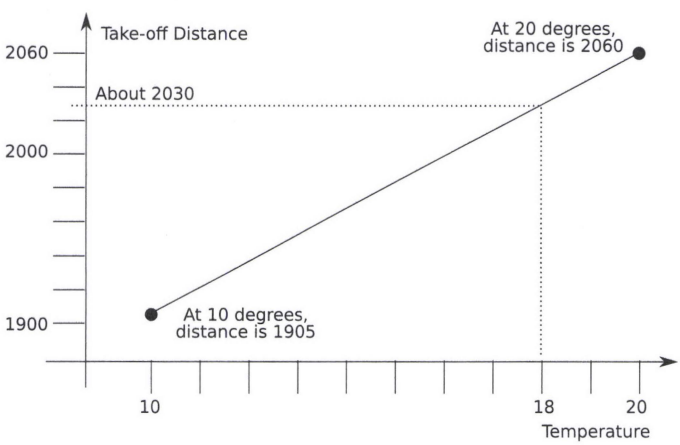

Figure D.1: Linear Interpolation

The steps are as follows:

- Plot the two points which you have on a suitable graph (see figure D.1)
- Draw a straight line between the points
- Read off the takeoff distance for any temperature (or the temperature for any takeoff distance)

In the example we read off a takeoff distance of about **2,030 ft** when the temperature is 18°C.

D.2 Method 2: Formula

This method is completely accurate but requires the memorisation of a formula:

$$Y = y_1 + \left(\frac{y_2 - y_1}{x_2 - x_1}\right)(X - x_1)$$

Here x_1 and x_2 are the two temperatures, y_1 and y_2 are the corresponding distances, X is the temperature for which you need to find the takeoff distance and Y is the unknown distance.

Using the numbers from the example above:

$$Y = 1905 + \left(\frac{2060 - 1905}{20 - 10}\right)(18 - 10) = 2029$$

so the takeoff distance is **2,029 ft.**

D.3 Method 3: Thinking

This is the standard technique. Normally it is much simpler than using the formula and much quicker than graphing. The reasoning is as follows:

- The difference between 20°C and 10°C is 10Cdeg
- The difference between 1,905 and 2,060 ft is 155 ft
- 18°C is 80% of the way from 10°C to 20°C
- 80% of 155 ft is 124 ft
- The answer is therefore 124 ft more than 1,905 (i.e. the answer is **2,029 ft**)

Note that in this example, the difference between the calculated answer of 2,029 ft and the answer obtained by taking the 20°C number (2,060 ft) is only 31 ft. A prudent pilot would have saved work by assuming 2,060 ft.

Appendix E

Disorientation: 178 Seconds To Live

This appendix is taken from a study carried out in 1993 by Verdon Kleimenhagen, Ron Keones, James Szajkovics and Ken Patz. The full report can be found at many places on the Internet. The underlying figures are themselves based on a 1954 study and can therefore possibly be considered suspect in the 21st century when much more emphasis is given to "hood" work during Private Pilot training. While the actual numbers are suspect, the scenario painted here is certainly one that can, and does, occur. There is a significant difference between flying with an instructor while wearing a hood (often permitting useful peripheral vision) and entering genuine cloud as the pilot-in-command.

A pilot should think about this scenario before pressing on into marginal weather.

E.1 The Situation

The sky is overcast and the visibility is poor. That reported five mile visibility looks more like two, and you can't judge the height of the overcast. Your altimeter tells you that you are at 1,500 ft but your map tells you that there's local terrain as high as 1,200 ft. There might be a tower nearby because you're not sure how far off course you are. But you've flown into worse weather than this, so press on.

E.2 Your Reaction

You find yourself unconsciously easing back just a bit on the controls to clear those towers. With no warning, you're in the soup. You peer so hard into the milky white mist that your eyes hurt. You fight the feeling in your stomach. You try to swallow, only to find your mouth dry. Now you realise you should have waited for better weather. The appointment was important, but not all that important. Somewhere a voice is saying, "You've had it – it's all over!"

E.3 You now have 178 seconds to live...

Your aircraft feels on even keel but your compass turns slowly. You push a little rudder and add a little pressure on the controls to stop the turn but this feels unnatural and you return the controls to their original position. This feels better but now your compass is turning a little faster and your airspeed is increasing slightly. You scan your instruments for help but what you see looks somewhat unfamiliar. You're sure that this is just a bad spot. You'll break out in a few minutes. (But you don't have a few minutes left.)

E.4 You now have 100 seconds to live...

You glance at your altimeter and you are shocked to see it unwinding. You're already down to 1,200 ft. Instinctively, you pull back on the controls but the altimeter still unwinds. The engine is into the red and the airspeed, nearly so.

E.5 You have 45 seconds to live...

Now you're sweating and shaking. There must be something wrong with the controls; pulling back only moves the airspeed indicator further into the red. You can hear the wind tearing at the aircraft.

E.6 You have 10 seconds to live...

Suddenly you see the ground. The trees rush up at you. You can see the horizon if you turn your head far enough but it's at a weird angle—you're almost inverted. You open your mouth to scream but...

...you just ran out of seconds.

Appendix F

Triangle of Velocities

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F.1 The Problem

The technique known as *Triangle of Velocities* is what your aviation calculator performs when given a question of the form:

- You wish to fly across the ground on a track of 340°.
- Your aircraft flies at 100 knots airspeed.
- The wind is forecast to be blowing from 280° at 25 knots.

In what direction should you point the aircraft and at what speed will you be travelling across the ground?

Exam Hint 40 *Before tackling one of these types of calculation in an examination, ensure that the desired track and wind direction are either both Magnetic bearings or both True bearings. It doesn't matter which they are, but they must both be the same.*

It is rare to need to perform one of these calculations manually: any aviation calculator and almost all handheld GPS units can do this sort of calculation much faster than a human with a piece of paper. However, for completeness, the manual method is described below. It can be useful because it gives a visual representation of what the calculators are silently doing.

F.2 Drawing the Triangle

Without the aid of an electronic calculator, you will need a piece of paper, a ruler and protractor. Carry out the following steps:

1. Somewhere close to the centre of the paper place a dot.

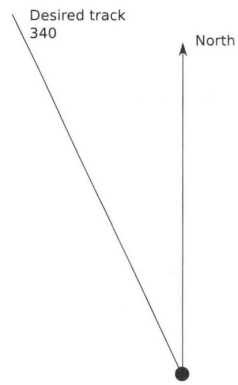

Figure F.1: Triangle of Velocities: Step 1

2. From the dot, draw a line to represent north and another to represent the desired track, in this case at 340°, as shown in figure F.1.

3. From the dot, draw a line to represent the wind speed. In this case, the wind is blowing *from* 280°, so we draw a line of length 25 units to represent the wind speed as shown in figure F.2. The units can be anything convenient to fit onto the page—inches, centimetres, millimetres, hands, furlongs, eights of an inch or whatever.

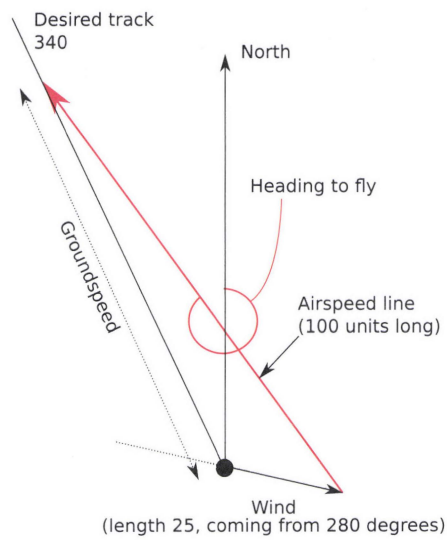

Figure F.2: Triangle of Velocities: Step 2

4. From the end of the wind line, draw a line of length 100 units (to represent your airspeed) with its head on the track line you drew in step 2.

5. Measure the distance from the dot to the end of the line you have just drawn. This represents your ground speed. In this case it will be just over 85 units long.

6. Measure the angle between the north line and the line you have just drawn. This represents the heading you need to fly. In this case it will be about 327°.

F.3 Using Trigonometry

If you are familiar with high-school trigonometry, you will recognise this as nothing more than an application of the *cosine rule* to adding vectors. In this case, applying the cosine rule:

$$\begin{aligned} 100^2 &= a^2 + 25^2 - 25 \times 2 \times cos(120°) \\ \implies 0 &= a^2 + 25a - 100^2 + 25^2 \\ \implies a &= \frac{-25 + \sqrt{25^2 + 4(100^2 - 25^2)}}{2} \\ \implies a &\approx 85.128 \end{aligned}$$

The ground speed is therefore approximately 85 knots. Although this calculation is straightforward, in an examination using an aviation calculator is certainly to be preferred.

Exercise 107 *You need to fly a track of* 090° *true and, at the altitude you intend to fly, the winds are forecast to be from* 170° *at 35 knots. Your true airspeed is 105 knots. Draw a triangle of velocities and from it estimate the heading you will need to fly and your expected ground speed.*

F.4 Answer to Exercise 107

Following the instructions above, place a dot near the centre of a piece of paper and draw a line to represent (true) north and your required track. Then draw a line of the correct length to represent the wind—see figure F.3 (a).

Now draw a line 105 units long to represent the aircraft's airspeed. Its tail must be at the tip of the wind arrow and its head on the track line.

Now it is easy to measure the ground speed along the track line (93 knots) and the required heading (109°). Whenever you draw one of these triangles make sure that you do a sanity check on the results. Here you have a headwind so you would expect a ground speed less than your airspeed and you have the wind coming from your right so you would expect to crab right a little. Both of these correspond with the answer.

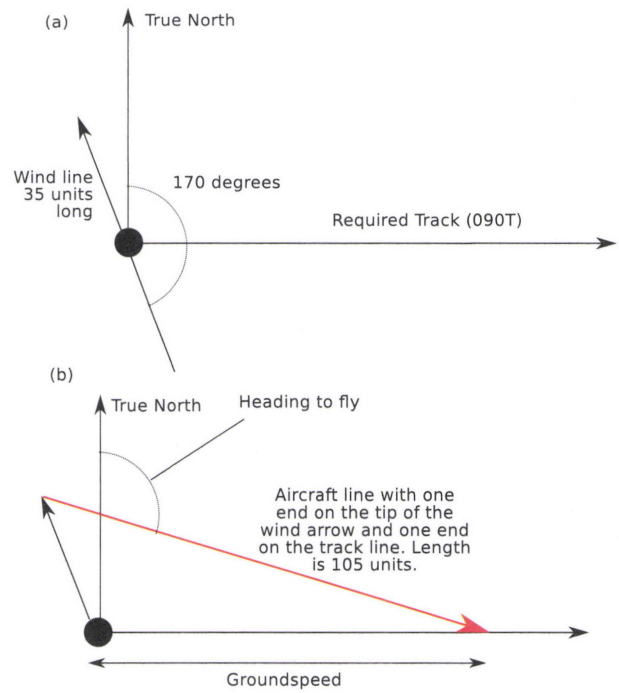

Figure F.3: Figure for Example 107

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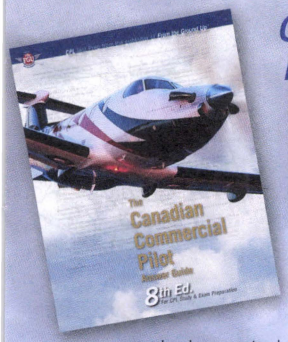

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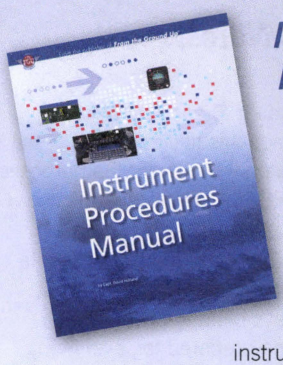
Setting itself even further apart, this new ***Canadian Commercial Pilot Answer Guide*** references the most important material available to students as they embark on their path towards professional aviation careers. ***From the Ground Up***, ***Flying Beyond***, the ***Canadian Aviation Regulations,*** the ***Aeronautical Information Manual***, the ***Flight Training Manual***, the ***Canada Flight Supplement***, and ***AWARE Aviation Weather*** are all referenced within this newly updated Study Guide.

As a long-established educational resource for students and flying schools across the country, the ***Canadian Commercial Pilot Answer Guide*** takes students through all the aeronautical subjects that they need to know to prepare for the writing of the CPL exam.

Seven chapters make up the bulk of this latest version of the title. They are: **Chapter 1** *Flight Operations*; **Chapter 2** *Navigation*; **Chapter 3** *General Knowledge*; **Chapter 4** *Theory of Flight*; **Chapter 5** *Meteorology*; **Chapter 6** *Weather Reports and Forecasts*; **Chapter 7** *Air Law*. **Chapter 8** provides, as always, a 100-Question *Sample Examination*. **Appendix A** contains *Notes on the Questions* that greatly enhance this publication's position as a learning and study resource without equal.

Author Chris Hobbs' meticulous work and exceptional explanations ensure that this title remains a foremost means for students to study and review essential subject matter to surpass Transport Canada's CPL standards.



Instrument Procedures Manual, 6th Edition

Our latest edition of this renowned instrument pilot textbook, the ***Instrument Procedures Manual, 6th Edition***, also known as the "***IPM***," sets the new standard for thoroughness, scale and scope on the advanced subject of instrument flying.

This latest edition of this prominent instrument flight rules (IFR) textbook consolidates its preeminent status. It is written to provide students, as well as experienced aviation professionals, with information on today's aircraft, satellite and ground-based instrument systems, departure, en route and approach procedures, and air traffic control regulations.

Nine chapters make up the bulk of this edition of this title. They include: *Physiological Factors Related to IFR Flight, Instrumentation and Navigation Systems, Instrument Flight Techniques, Air Traffic Services, IFR Flight Procedures,* and *Rotor Wing*. Content also includes chapters on *Pilot Performance, Automation and Technology,* and *International Procedures*.

Readers will also find seven extensive Appendices in the new ***IPM***, as well as a very thorough Index. Every phase of flight, from pre-flight to landing, is discussed in terms of a safe and efficient IFR operation.

The author of the ***IPM***, Dave Holland, amassed over 19,000 hours of flight time during a flying career that spanned over 30 years. He was an Airbus A330 Captain, and an Airbus Check Captain at Air Canada. He was a Transport Canada Pilot Examiner, and a Transport Canada Inspector. He also served in the Canadian Armed Forces as a Captain and Instructor on C130 Hercules aircraft. Now retired from the airlines, he remains active and in demand as president of Aerosolutions through which he does consultancy work in advanced aviation training.

Long considered the authoritative textbook on instrument flying, the ***Instrument Procedures Manual*** is crucial, and essential, reading for every serious pilot, be they student or experienced professional.

If you want to know everything, and more, about flying IFR, the ***Instrument Procedures Manual*** is the book to have.

Ask your local flying school for details, visit your local pilot supply shop, or visit us on the web to obtain information about buying these titles.

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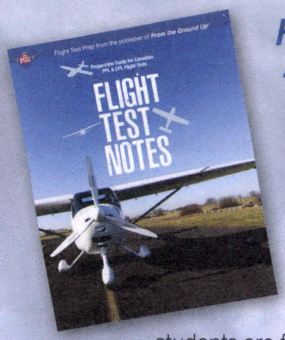


Flight Test Notes, 4th Edition

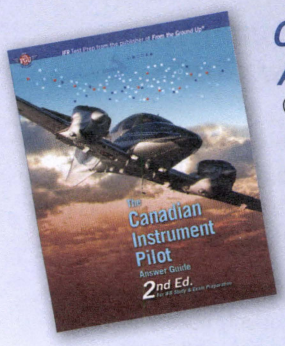
Feedback regarding ***Flight Test Notes*** continues to place this title at the top of the list of study material written for the purposes of PPL and CPL flight test preparation. Unique in its purpose, it is universally described as being "perfect" for the role for which it has been developed. That role has always been to ensure that students are fully aware of, and prepared for, everything that their examiner expects of them during the flight test.

Jitters and nerves can detract the most skillful of students from achieving the results of which they are capable. Therefore, knowledge of the flight test process ahead of time, combined with systematic preparation prior to its undertaking, eases the stress and butterflies. By being the most prepared one can be, students can eliminate surprises. That's entirely what ***Flight Test Notes*** is about.

Written for the benefit of all student flight test prospects, ***Flight Test Notes*** takes readers step-by-step through every exercise that they'll encounter in their flight test. Flight exercises are analyzed in detail with the key objective being to describe the level of performance that examiners expect from students as they perform to maximize their grade.

This latest ***Flight Test Notes*** combines its clear review of Transport Canada's criteria with a cross-section of questions and answers, detailed "do's and don'ts", and in-depth analyses of common mistakes with suggestions as to how to avoid them. Every phase of the examination, from the pre-flight inspection through to takeoffs, climbs, turns, circuits, stalls, diversions, forced approaches, landings, emergencies and everything else that an examiner wants to see a candidate perform, is covered in ***Flight Test Notes***.

Flight Test Notes has been recognized as an excellent exam preparation resource that thoroughly describes what to anticipate during flight tests. Now into its third decade of availability, it has become a cornerstone for flight training in Canada, a test prep resource that eases the path for students seeking not just their licence to fly but who are also seeking proficiency at the highest level achievable.



Canadian Instrument Pilot Answer Guide, 2nd Edition

Our latest edition of this study guide for students learning instrument flying procedures, the ***Canadian Instrument Pilot Answer Guide*** is written to prepare students thoroughly for their IFR exam. The unique format that characterizes our popular PPL and CPL exam prep material also forms the backbone of this new IFR study reso urce.

This latest edition of the ***Canadian Instrument Pilot Answer Guide*** has been written from scratch. As with its PPL and CPL study guide siblings, the ***Canadian Instrument Pilot Answer Guide*** combines advanced and challenging questions with detailed explanations for each and every question and answer that make up its content. IFR students can, thus, benefit enormously from this enhanced format leading up to their written IFR exam. While using the ***Instrument Procedures Manual*** as their primary reference resource, students can also refer to the study guide's in-depth explanations to augment their understanding of IFR concepts.

Resources from which to draw upon to tackle content in this ***Canadian Instrument Pilot Answer Guide*** include the ***Instrument Procedures Manual***, ***From the Ground Up***, the ***Canadian Aviation Regulations***, the ***Aeronautical Information Manual***, the ***Canada Flight Supplement***, and ***AWARE Aviation Weather***. Combined with the aforementioned exceptional explanations for each answer, the content of this ***Canadian Instrument Pilot Answer Guide*** provides the most thorough of means by which IFR students can study and review essential subject matter to achieve the high standards required of IFR pilots.

Companioned primarily to the highly regarded ***Instrument Procedures Manual***, the ***Canadian Instrument Pilot Answer Guide*** takes readers through the subjects they'll encounter in their written Instrument Rating exam. These include: *Air Law & Procedures, Meteorology, Instrumentation, Navigation, Radio Aids, Human Factors* and *Airmanship*. A 50-question *Sample Examination* is found within the book, as is helpful reference material for all pertinent questions. The author's extensive notes associated to the questions advance and solidify reader understanding of study guide content.

Get the best from your IFR studies by amplifying and consolidating your instrument procedures' knowledge with the ***Canadian Instrument Pilot Answer Guide***.

Ask your local flying school for details, visit your local pilot supply shop, or visit us on the web to obtain information about buying these titles.

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Flying Beyond:
The Canadian Commercial Pilot Textbook

From the publisher of the acclaimed textbook, ***From the Ground Up,*** this Third Edition of ***Flying Beyond: The Canadian Commercial Pilot Textbook*** is the perfect educational segue into the higher standards required of students seeking their commercial pilot licence.

Authored by experienced and respected Canadian ground school instructor, Chris Hobbs, ***Flying Beyond*** delves deeply into all the subject areas that readers need to know to pass the commercial written examination. While conscientiously fulfilling this latter requirement, it is also written to take students forward on a career path as highly-skilled, knowledgeable, and thoroughly-educated professional aviators.

The topics in ***Flying Beyond*** are presented in the order given in Transport Canada's syllabus. Subjects include: Human Factors (Psychological and Physiological), Theory of Flight, Airframes and Engines, Aircraft Systems, Flight Instruments, Meteorology, Weather Reports and Forecasting, Pilot Navigation and Radio Navigation, Flight Operations, Air Law, and more.

Each chapter is enhanced with compelling anecdotes that serve as excellent "real-world" learning tools that put subject matter into greater perspective for readers. Furthermore, examples abound throughout the book to further consolidate the understanding of subject matter. Also, frequently placed "exam hints" direct readers to pay special attention so as to be better prepared to take the written commercial test.

Whether seeking to acquire the basic knowledge necessary to earn a commercial licence, or setting out on a career path in aviation, ***Flying Beyond*** serves both needs comprehensively. For students seeking more, ***Flying Beyond*** provides it: beyond the scope of the private licence, and deeply into the broader knowledge-base required to step into the commercial flying realm.

Flying Beyond, 3rd Edition is the starting point to launch students into the world of the professional pilot.

New horizons are found here!

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